Habituating Control Strategies for Process Control

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By "reverse engineering" the functions of a specific biological system, habituating control strategies are developed for process control applications. A habituating control system has the distinguishing property of more manipulated inputs than controlled outputs; with the inputs differing significantly in their dynamic effect on the outputs and in the relative costs of manipulating each one. A habituating controller coordinates the use of all the available inputs to achieve high-performance output objectives while simultaneously minimizing the cost of taking control action.

The "baroreceptor reflex," the control system responsible for short-term blood pressure regulation, provides the biological paradigm for the analysis and design of the habituating control structure. Its main characteristics are discussed from a process control perspective, indicating that the robust, high-performance control, characteristic of biological systems is partly due to such habituating control architectures. The broad range of potential process applications is illustrated with two examples. Two basic strategies are presented for the design of habituating controllers for linear systems with two inputs and one output: the direct synthesis approach and the model predictive approach. Compared to previous techniques for multiple-input, single-output systems, the direct synthesis strategy is straightforward and systematic. Simulation results demonstrate the superior performance of habituating control compared to conventional techniques for which the number of inputs and outputs are equal.

Introduction

Many control problems similar to those encountered in the process industries have been solved effectively in biological systems. By studying and understanding such biological control systems, it should be possible to mimic their functions in chemical process applications. This strategy of "reverse engineering" biological control system functions thus provides an alternative approach to the design of effective process control systems.

One of the strategies commonly employed by biological control systems involves the deliberate use of more manipulated inputs than the outputs to be controlled (Grodins, 1963; Jones, 1973). By design, the dynamic effects of the inputs often vary significantly due to differences in chemical and electrical pathways; in addition, each input has an associated cost that depends on both the short-term and long-term effects of the control action. In many of these biological control systems, the inputs with the most direct effect on critical physiological variables are expensive, while the relatively cheaper inputs have a less direct effect. Under these circumstances, a *habituating control strategy* is used to coordinate how the available inputs should be manipulated in order to maintain the outputs at their setpoints while minimizing the overall cost of control action. As discussed in the following section, the cardiovascular system employs such a habituating control strategy for regulating arterial blood pressure.

The primary thesis of this article is that similar habituating control strategies can be employed in chemical process applications. For example, many process control systems employ

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only slow, "cheap" variables as the manipulated inputs, although additional fast, but "expensive" inputs are available. These potentially useful inputs are often disregarded due to cost considerations, or because they are subject to more process restrictions. Moreover, these inputs represent additional degrees of freedom not present in conventional process control systems, and additional objectives must be specified to obtain a well-defined control problem. In a habituating control system, the fast (secondary) inputs can be used to track setpoint changes and reject disturbances rapidly. As the slower (primary) inputs begin to affect the outputs, the fast inputs can habituate by slowly returning to their desired values. Because the expensive secondary inputs are not used at steady state, improved performance can be obtained with little additional cost. Superior control may also be obtained for processes in which nonminimum-phase elements limit the performance achievable with the primary inputs. Because multiple inputs are employed, the habituating control scheme can be expected to yield superior robustness in the event of controller saturation or failure as compared to conventional single-input, single-output (SISO) control techniques.

In this article, habituating control strategies are developed and evaluated for single-output, linear processes. The controller architecture and design are motivated by the habituating control system responsible for mammalian blood pressure regulation. Two physical processes that can benefit from habituating control are identified, and two basic controller design strategies are presented. In the direct synthesis approach, the desired closed-loop behavior is specified and the controller required to meet this objective is derived directly. The model predictive control (MPC) technique is based on a simple, but important, modification of the quadratic objective function employed in conventional MPC techniques (Prett and Garcia, 1988). Simulation results for three linear systems demonstrate the significantly improved performance that can be achieved with the habituating control strategies as compared to conventional SISO control techniques.

Habituating control strategy vs. related control techniques

Techniques that are similar to the habituating control scheme have been proposed in the standard control literature: these include valve position control (Shinskey, 1978; Luyben, 1990); coordinated control (Popiel et al., 1986; Chia and Brosilow, 1991); parallel control (Balchen and Mumme, 1988); and H_∞ control (Williams et al., 1992; Medanic, 1993). Like the habituating control approach, these control strategies employ more manipulated inputs than controlled outputs. However, there are several important differences between the habituating control strategy presented in this article and these related control schemes.

1. Our primary objectives are to understand and then to mimic the functions of a biological control system for process monitoring, modeling, and control applications; the habituating control strategy therefore is a translation of a biological control solution for appropriate process control problems. By contrast, these other techniques are direct control solutions to control problems.

2. The habituating control strategy is formulated to exploit *specific* characteristics and operating objectives of a process with two *different* types of manipulated variables: (i) a slow, cheap type; (ii) a fast, expensive type. By contrast, H_∞ control techniques were developed for a more general class of systems; therefore, fundamental differences in the dynamic effects and costs of the manipulated inputs are not easily exploited. This point is illustrated quite clearly by Williams et al. (1992). In obtaining an acceptable H_∞ controller for a system with one slow, cheap input and one fast, expensive input, significant design effort is required to select appropriate frequency domain weighting functions used in the H_∞ cost function (Williams et al., 1992).

3. The *habituating control architectures* are generalizations of the series (Luyben, 1990) and the parallel (Popiel et al., 1986; Balchen and Mumme, 1988) control structures employed in other approaches.

4. The habituating control strategy is supported by a *systematic* controller synthesis methodology. By contrast, the design procedures proposed for the valve position, coordinated, and parallel control techniques are largely *ad hoc*, especially for nonminimum-phase systems.

5. The effects of controller saturation and actuator failure on the habituating control strategy are analyzed, while these important issues are neglected in most other studies.

The rest of the article is organized as follows: first, we give a description of the habituating control system which regulates arterial blood pressure and discuss two potential process applications. Next, two design strategies are presented for linear systems with two manipulated inputs and one controlled output: the *direct synthesis* approach and the *model predictive control* approach. Finally, three simulation examples presented compare the habituating control strategies to conventional SISO control techniques.

Motivation and Applications

Habituating control in the cardiovascular system

The cardiovascular system plays a critical role in *homeostasis*, a biological term that refers to the coordinated actions that maintain the equilibrium state of a living organism. Regulation of the cardiovascular system is achieved by a number of distinct control systems, or "reflexes." The *baroreceptor reflex* is primarily responsible for the short-term regulation of arterial blood pressure (Sagawa, 1983; Kumada et al., 1990). The blood pressure in the main arteries is transduced by stretch-sensitive neurons known as arterial baroreceptors (Kirchheim, 1976). In the central nervous system (CNS), baroreceptor discharges are integrated with other signals that reflect cardiovascular demand (Mifflin and Felder, 1990; Paton et al., 1991). The integrated sensory information is used to regulate heart function and blood flow, which in turn affect the blood pressure (Karemaker, 1987).

A simplified block diagrammatic representation of the baroreceptor reflex is shown in Figure 1. The objective of the control system is to maintain the arterial blood pressure at a desired value. Blood pressure measurements are provided by baroreceptor neurons located within the carotid sinus and aortic arch. Two distinct controllers in the CNS, the sympathetic and parasympathetic systems, receive baroreceptor discharges. The controllers compare these discharges to a desired blood pressure signal determined by a variety of factors that affect cardiorespiratory performance (Spyer, 1990). The sympathetic and parasympathetic systems affect the cardio-

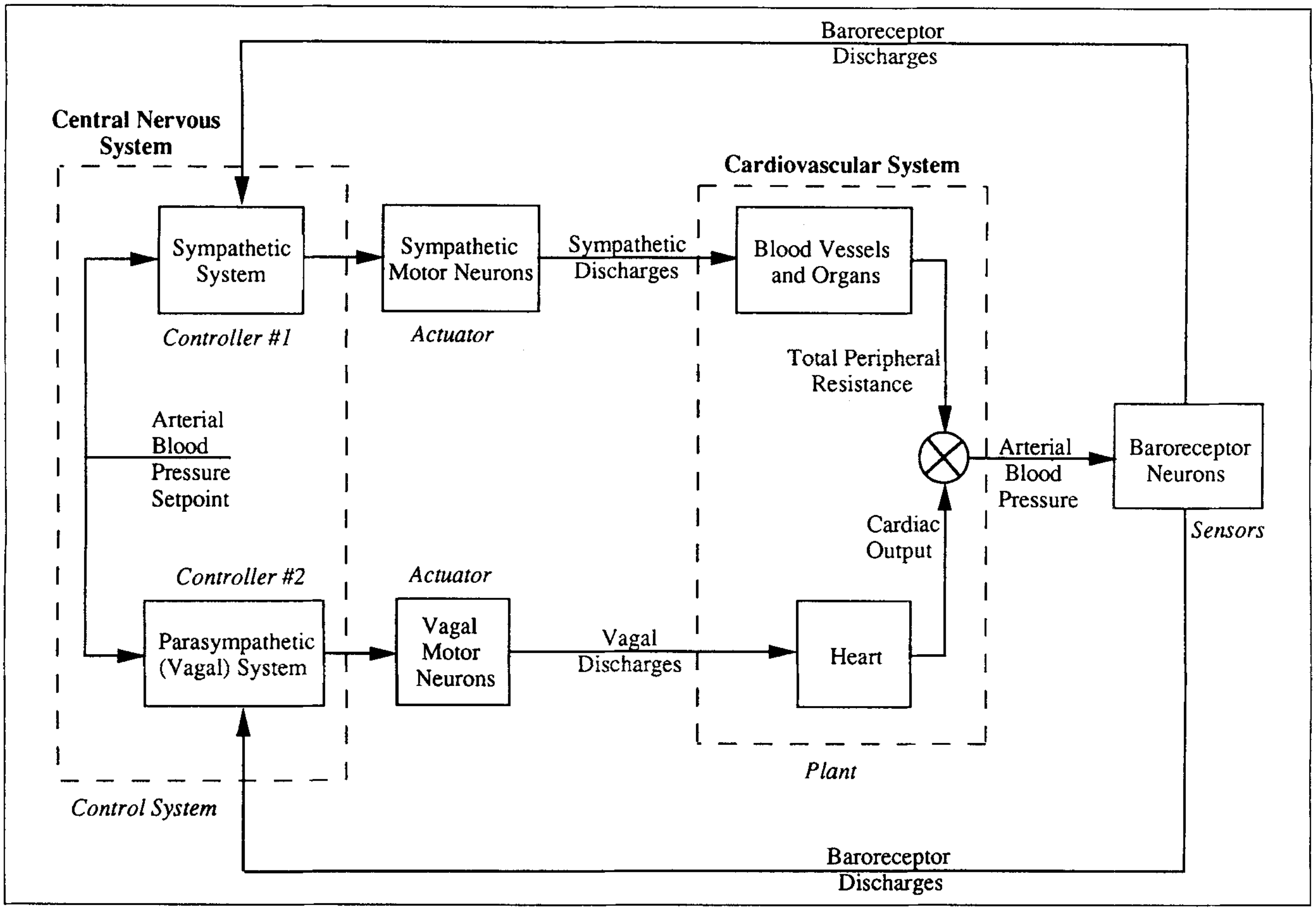

Figure 1. Baroreceptor reflex.

vascular system via sympathetic and vagal postganglionic motor neurons, respectively. Although the heart is affected by sympathetic discharges (Kumada et al., 1990), the primary couplings are between the parasympathetic system and cardiac output, and between the sympathetic system and total peripheral resistance. The arterial blood pressure is obtained as the product of the cardiac output and total peripheral resistance.

The effect of the parasympathetic system on arterial pressure is quite rapid, while that of the sympathetic system is comparatively slow. In modeling the closed-loop response of each of the two control systems to a step disturbance in the carotid sinus pressure of the dog, Kumada et al. (1990) obtained the following results. Using a first-order-plus-deadtime model structure, the time constant and time delay for the sympathetic system response were estimated, respectively, as $10 \leq \tau_1 \leq 80$ s, $2 \leq \theta_1 \leq 4.5$ s; for the parasympathetic response, the corresponding estimates ($7 \leq \tau_2 \leq 25$ s, $0.6 \leq \theta_2 \leq 1.2$ s) are comparatively small. However, even though the parasympathetic system is able to affect the arterial pressure quite rapidly, sustained variations in the cardiac output are undesirably "expensive," whereas long-term variations in the peripheral resistance are more acceptable. Cardiac output is therefore an expensive manipulated variable as compared to the peripheral resistance.

The brain implements *habituating control* by coordinating the use of the sympathetic and parasympathetic systems in order to provide high-performance control while minimizing the long-term cost of the control actions. For instance, consider a blood pressure decrease caused by an external disturbance (such as standing up). The parasympathetic system induces a rapid increase in blood pressure by enhancing cardiac output. A significantly slower increase in blood pressure is caused by the sympathetic system raising peripheral resistance. As the effects of increased peripheral resistance on the blood pressure become more pronounced, the parasympathetic controller *habituates* by returning cardiac output to its previous steady-state value.

The baroreceptor reflex therefore provides an excellent biological paradigm for the development of habituating control strategies for process control applications. As indicated in italics in Figure 1, the components of the system have well-defined control analogs: the CNS is the "controller," the sympathetic and vagal postganglionic motor neurons are the "actuators," the cardiovascular system is the "plant," and the baroreceptors are the "sensors." More importantly, many processes possess manipulated inputs that differ in terms of their dynamic effects on the outputs and relative costs.

Process control applications

In the two potential process applications discussed below

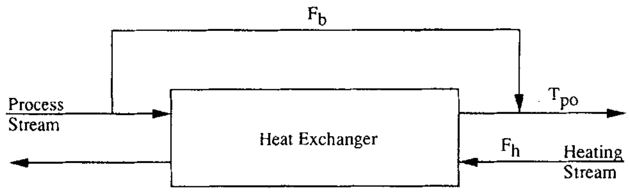

Figure 2. Heat exchanger with bypass.

(1) control system performance is limited by the nature of the dynamic effect exerted on the output by the primary manipulated input, but a secondary input is available whose effect on the output is characterized by superior dynamics; (2) however, the long-term cost associated with the "superior" secondary input is greater than that associated with the primary input. Processes with such characteristics are ideally suited to benefit from habituating control strategies.

Heat Exchanger. Consider the heat exchanger with bypass shown in Figure 2. The control objective is to regulate the outlet temperature of the process stream, T_{po}. There are two manipulated inputs available: the heating stream flow rate (F_h) and the process stream bypass flow rate (F_b). The bypass flow F_b has a much more rapid and direct effect on T_{po} than does F_h. In order to minimize energy costs and maintain sufficient flexibility in the inputs, it is desirable to maintain F_b near a predetermined setpoint. Hence, F_h can be viewed as the primary input and F_b as the secondary input. Because of the differences in the dynamic effects and costs associated with the two inputs, this process can benefit from habituating control. A similar heat exchanger example has been considered in the context of parallel control (Balchen and Mumme, 1988).

Polymerization Process. A simplified diagram of a process for manufacturing certain acrylic resins is shown in Figure 3. The process consists of a continuous stirred tank polymerization reactor and an overhead cooling water exchanger. The feed to the reactor consists of monomer, initiator, and solvent. The exchanger is used to condense solvent and monomer vapors, and a cooling water jacket is available to cool the reactor contents. The process also includes a vent line for condensibles and a nitrogen admission line that can be used to regulate the reactor pressure P. One of the control objectives is to control the reactor temperature, T; the cooling water flow rate, F_j, and P (which can be changed almost instantaneously via nitrogen admission) are the principal manipulated variables. The reactor pressure P has a much more rapid and direct effect on T than does F_j. However, because significant and/or extended pressure fluctuations affect the reaction kinetics adversely, it is desirable to maintain P near its setpoint. A habituating control strategy can be developed for this process by considering F_j as the primary input and P as the secondary input. A similar reactor example has been discussed by Luyben (1990) as a potential application of valve position control.

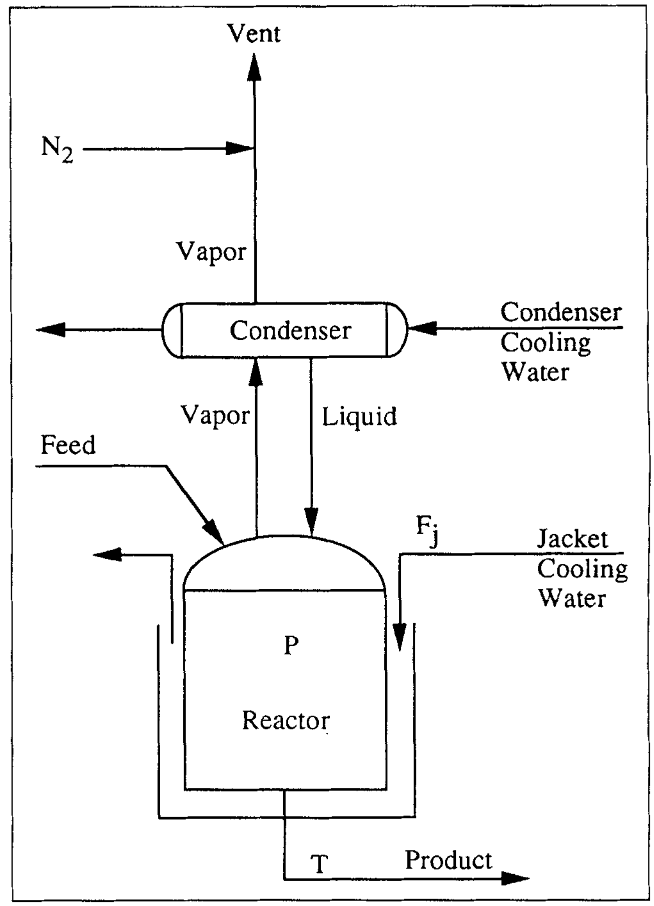

Figure 3. Polymerization process.

Habituating Controller Design

In this section, two design strategies for habituating controllers are presented. For simplicity, only linear process models with two manipulated inputs and one controlled output are considered. In the *direct synthesis* approach, the controller is synthesized to achieve desired closed-loop behavior as represented by prescribed transfer functions. Two alternative design techniques are proposed depending on the minimum phase characteristics of the transfer function between the primary input and controlled output. In the *MPC* formulation, the quadratic objective function employed in existing MPC techniques (Prett and Garcia, 1988; Garcia et al., 1989) is modified to include a penalty on the deviation of the secondary input from its setpoint. The tolerance of each approach to controller saturation and failure is considered.

Direct synthesis approach

For simplicity, we will restrict the discussion to single-output, transfer function models of the form,

$$y(s) = g_1(s)u_1(s) + g_2(s)u_2(s) + g_3(s)d(s) \qquad (1)$$

where y is the controlled output, u_1 and u_2 are the primary and secondary inputs, respectively, and d is an unmeasured disturbance. Two alternative controller synthesis procedures are presented for minimum phase and nonminimum-phase-transfer functions g_1. Because u_2 is chosen as a result of its favorable dynamic effects on y, the transfer function g_2 is assumed to be minimum phase. Additionally, the three model transfer functions (g_1, g_2, g_3) are assumed to be stable.

These assumptions are made in order to focus on the essentials; if g_2 contains nonminimum-phase elements, the habituating control approach is still applicable as long as g_2 is "less" nonminimum phase than g_1. (For instance, the approach is applicable to systems in which the time delay in g_2 is less than the time delay in g_1 with slight, but obvious, modifications to the controller design procedures presented below.) Also by employing stabilizing filters such as those discussed in Morari and Zafiriou (1989), it is possible to extend the technique to unstable systems.

Control Objectives. Because there are two manipulated inputs and one controlled output in Eq. 1, the combination of control actions required to produce the desired output y_{sp} at steady state is nonunique. Additional objectives are therefore required to obtain a well-defined control problem. In habituating control problems such as those described earlier, the secondary input should also track a desired value ($u_{2_{sp}}$) asymptotically. The desired control objectives are therefore as follows:

1. Obtain a desired transfer function $g_{y_d}(s)$ between y_{sp} and y.
2. Obtain a desired transfer function $g_{u_d}(s)$ between $u_{2_{sp}}$ and u_2.
3. Obtain a decoupled response between $u_{2_{sp}}$ and y.
4. Achieve asymptotic tracking of the y_{sp} and $u_{2_{sp}}$ despite plant/model mismatch.
5. Ensure nominal closed-loop stability.

The closed-loop transfer function matrix should therefore have the form,

$$\begin{bmatrix} y \\ u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} g_{y_d} & 0 & * \\ * & * & * \\ * & g_{u_d} & * \end{bmatrix} \begin{bmatrix} y_{sp} \\ u_{2_{sp}} \\ d \end{bmatrix} \tag{2}$$

where each asterisk (*) denotes a stable transfer function; g_{yd} and g_{ud} have the property that $g_{yd}(0) = g_{ud}(0) = 1$. In order to achieve the fourth property, the transfer functions y/d, u_2/y_{sp}, and u_2/d must have zero steady-state gain. The asymptotic requirements placed on the transfer functions involving the secondary input u_2 are unique features of the habituating control strategy.

Control Architectures. Two alternative habituating control architectures are shown in Figure 4. Figure 4a is called the "series" structure because the input to the primary controller (g'_{c_1}) is the error between u_2 and its setpoint. In other words, u_1 is "driven" by deviations of u_2 from its setpoint. The job of responding to disturbances is initiated by u_2, with u_1 "kicking in" only as a result of a nonzero error between u_2 and $u_{2_{sp}}$. The series control architecture is a generalization of structures proposed for valve position control (Shinskey, 1978; Luyben, 1990).

In the series structure, the two controllers have the form,

$$u_1(s) = g'_{c_1}(s)\left[u_{2_{sp}}(s) - u_2(s)\right] \tag{3}$$

$$u_2(s) = g'_{c_{21}}(s)[y_{sp}(s) - y(s)] + g'_{c_{22}}(s)u_{2_{sp}}(s) \tag{4}$$

where the prime (′) superscript denotes the series approach.

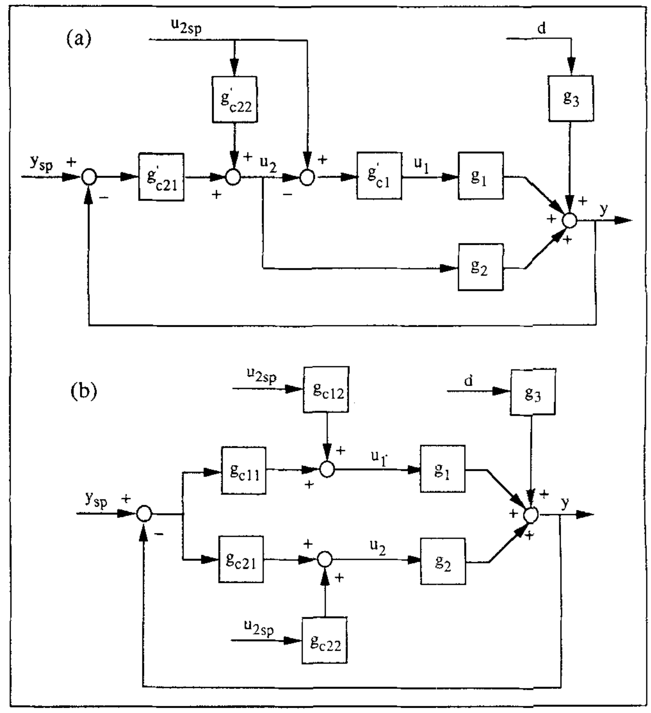

Figure 4. (a) Series; (b) parallel habituating control architectures.

If the controller transfer functions are chosen such that,

$$g'_{c_1}(0) = \infty; \quad g'_{c_{21}}(0) < \infty; \quad g'_{c_{22}}(0) = 1, \tag{5}$$

then asymptotic tracking of the setpoints y_{sp} and $u_{2_{sp}}$ will be achieved even in the presence of plant/model mismatch (assuming that the closed-loop system is asymptotically stable).

Figure 4b is called the "parallel" architecture because both the primary controller (composed of $g_{c_{11}}$ and $g_{c_{12}}$) and secondary controller (composed of $g_{c_{21}}$ and $g_{c_{22}}$) receive the error between y and y_{sp} as an input. Therefore, each controller responds to setpoint changes and disturbances independently of the other controller. The controllers in the parallel architecture have the form:

$$u_1(s) = g_{c_{11}}(s)[y_{sp}(s) - y(s)] + g_{c_{12}}(s)u_{2_{sp}}(s) \tag{6}$$

$$u_2(s) = g_{c_{21}}(s)[y_{sp}(s) - y(s)] + g_{c_{22}}(s)u_{2_{sp}}(s). \tag{7}$$

In order to ensure asymptotic tracking of the setpoints, the controller transfer functions must be chosen such that

$$g_{c_{11}}(0) = \infty; \quad g_{c_{12}}(0) < \infty; \quad g_{c_{21}}(0) < \infty; \quad g_{c_{22}}(0) = 1. \tag{8}$$

The parallel control architecture represents a generalization of structures proposed for coordinated control (Popiel et al., 1986) and parallel control (Balchem and Mumme, 1988).

The transfer functions in the two architectures shown in Figure 4 are related as

$$g_{c_{11}}(s) = -g'_{c_1}g'_{c_{21}}; \quad g_{c_{12}}(s) = [1 - g'_{c_{22}}(s)]g'_{c_1} \tag{9}$$

$$g_{c_{21}}(s) = g'_{c_{21}}; \quad g_{c_{22}}(s) = g'_{c_{22}}(s). \tag{10}$$

The parallel architecture can always be obtained from the series architecture by choosing the transfer functions as in Eqs. 9 and 10. However, the series structure can be obtained from the parallel structure only if the following relation is satisfied:

$$g_{c_{21}}(s) = -\frac{[1 - g_{c_{22}}(s)]g_{c_{11}}(s)}{g_{c_{12}}(s)}. \tag{11}$$

If Eq. 11 does not hold, the parallel architecture has an additional controller transfer function, $g_{c_{21}}(s)$, which is not present in the series structure. Because of this additional degree of freedom, the parallel architecture is more general.

The parallel architecture in Figure 4a has four independent controller transfer functions. Because the controller has access to three signals (y, y_{sp}, $u_{2_{sp}}$) and manipulates two inputs (u_1, u_2), there are actually 6 degrees of freedom available. These two additional degrees of freedom are not used by the parallel controller because y and y_{sp} are combined into a single error signal ($y_{sp} - y$). This approach is appropriate if the dynamic characteristics of y_{sp} and $u_{2_{sp}}$ are similar to those of d. If this is not the case, a habituating controller architecture that employs the two additional degrees of freedom could be developed as in internal model control (Morari and Zafiriou, 1989). However, for the sake of brevity we will not consider this case. The series architecture has only three independent controller transfer functions as compared to the four transfer functions in the parallel structure. Despite this lost degree of freedom, the series architecture is more advantageous in certain cases, as will be discussed below.

Note that the baroreceptor reflex depicted in Figure 1 employs a parallel architecture similar to that shown in Figure 4b. Because the parallel structure is very similar to the reflex architecture and is more general than the series structure, the direct synthesis design approach presented below is based on the parallel architecture. However, the series structure provides a more transparent controller parameterization when the transfer function g_1 is nonminimum phase. In this case, the controller is *designed* using the series architecture and *implemented* with the parallel architecture, but it should be kept in mind that this approach results in the lost degree of freedom, as already mentioned earlier.

Design for Minimum-Phase Systems. In the first direct synthesis strategy, the parallel architecture is employed and the transfer function g_1 is assumed to be minimum phase. The model in Eq. 1 and controller in Eqs. 6 and 7 yield the following closed-loop system:

$$y = \frac{g_1 g_{c_{11}} + g_2 g_{c_{21}}}{1 + g_1 g_{c_{11}} + g_2 g_{c_{21}}} y_{sp} + \frac{g_1 g_{c_{12}} + g_2 g_{c_{22}}}{1 + g_1 g_{c_{11}} + g_2 g_{c_{21}}} u_{2_{sp}} + \frac{g_3}{1 + g_1 g_{c_{11}} + g_2 g_{c_{21}}} d \tag{12}$$

where the Laplace variable s has been omitted for convenience. Properties 1 and 3 listed earlier hold if

$$\frac{g_1 g_{c_{11}} + g_2 g_{c_{21}}}{1 + g_1 g_{c_{11}} + g_2 g_{c_{21}}} = g_{yd} \tag{13}$$

$$g_1 g_{c_{12}} + g_2 g_{c_{22}} = 0. \tag{14}$$

Because g_1 is minimum phase by assumption, these two control objectives can be achieved by designing the primary controller as

$$g_{c_{11}} = \frac{g_{y_d} - (1 - g_{y_d}) g_2 g_{c_{21}}}{(1 - g_{yd}) g_1}; \quad g_{c_{12}} = -\frac{g_2}{g_1} g_{c_{22}}. \tag{15}$$

Because Eq. 15 decouples the output y from the secondary input setpoint $u_{2_{sp}}$, it follows from Eq. 7 that the second property is obtained if

$$g_{c_{22}} = g_{ud}. \tag{16}$$

By combining Eq. 1 and Eqs. 15 and 16, it is easy to show that the nominal closed-loop system has the following form:

$$\begin{bmatrix} y \\ u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} g_{y_d} & 0 & (1 - g_{y_d}) g_3 \\ \frac{g_{y_d} - (1 - g_{y_d}) g_2 g_{c_{21}}}{g_1} & -\left(\frac{g_2}{g_1}\right) g_{ud} & -\left(\frac{g_{yd} - (1 - g_{y_d}) g_2 g_{c_{21}}}{g_1}\right) g_3 \\ (1 - g_{yd}) g_{c_{21}} & g_{u_d} & -(1 - g_{yd}) g_3 g_{c_{21}} \end{bmatrix} \begin{bmatrix} y_{sp} \\ u_{2_{sp}} \\ d \end{bmatrix}. \tag{17}$$

Because the transfer functions y/d, u_2/y_{sp}, and u_2/d have zero steady-state gain, the fourth property of asymptotic tracking is achieved. Assuming g_1 is minimum phase, the final property of nominal closed-loop stability is obtained for any stable transfer functions g_{y_d}, g_{u_d}, and $g_{c_{21}}$. By combining Eqs. 11, 15, and 16, it is easy to show that the habituating controller can be implemented in the series architecture shown in Figure 4a if

$$g'_{c_{21}} = \frac{(1 - g_{u_d}) g_{y_d}}{(1 - g_{y_d}) g_2}. \tag{18}$$

The transfer function g_{y_d} can be tuned according to the dynamics of the secondary transfer function g_2. Thus, the habituating control approach offers the possibility of significantly improved performance as compared to SISO control schemes in which g_{y_d} is tuned according to the dynamics of the primary transfer function g_1. Because the output is completely decoupled from $u_{2_{sp}}$, the primary controller may be overly aggressive for $u_{2_{sp}}$ changes if g_{u_d} is chosen to have similar dynamics as g_2. If the dynamics associated with the primary input are significantly slower than those associated with the secondary input, more reasonable control moves will be generated if g_{u_d} is chosen according to the dynamics of g_1. Note that $g_{c_{21}}$ can be used to tune the responses of the two inputs to changes in y_{sp} and d.

Design for Nonminimum-Phase Systems. If the transfer function g_1 contains nonminimum-phase elements (time delays and/or right-half-plane zeros), the habituating controller in Eqs. 15 and 16 cannot be employed for obvious reasons. In this case, the alternative design procedure presented below may be used. The controller synthesis is based on the series architecture in Figure 4a because it provides a more transparent parameterization of the controller. However, the habituating controller is actually implemented in the parallel structure shown in Figure 4b.

The following closed-loop system is obtained by combining the model in Eq. 1 with the controller in Eqs. 3 and 4,

$$y = \frac{(g_2 - g_1 g_{c_1}) g_{c_{21}}}{1+(g_2 - g_1 g_{c1}) g_{c_{21}}} y_{sp} + \frac{(g_2 - g_1 g_{c_1}) g_{c_{22}} + g_1 g_{c_1}}{1+(g_2 - g_1 g_{c_1}) g_{c_{21}}} u_{2_{sp}} + \frac{g_3}{1+(g_2 - g_1 g_{c_1}) g_{c_{21}}} d \quad (19)$$

where the prime (′) superscript has been omitted for convenience. The first and third control objectives listed previously are achieved if

$$\frac{(g_2 - g_1 g_{c_1}) g_{c_{21}}}{1+(g_2 - g_1 g_{c_1}) g_{c_{21}}} = g_{y_d} \quad (20)$$

$$(g_2 - g_1 g_{c_1}) g_{c_{22}} + g_1 g_{c_1} = 0. \quad (21)$$

Equations 20 and 21 can be solved for $g_{c_{21}}$ and g_{c_1}, respectively:

$$g_{c_{21}} = \frac{g_{y_d}}{(1-g_{y_d})(g_2 - g_1 g_{c_1})} \quad (22)$$

$$g_{c_1} = -\frac{g_2 g_{c_{22}}}{(1-g_{c_{22}}) g_1}. \quad (23)$$

Note that g_{c_1} contains the inverse of the nonminimum-phase transfer function g_1 and will be unstable and/or noncausal unless $g_{c_{22}}$ is designed appropriately. Hence, $g_{c_{22}}$ cannot be chosen as in Eq. 16 and the second property that $u_2/u_{2_{sp}} = g_{u_d}$ must be partially sacrificed. For most process control applications this approach should be acceptable because changes in $u_{2_{sp}}$ will be infrequent as compared to y_{sp} changes. Closed-loop stability and asymptotic tracking of $u_{2_{sp}}$ can be achieved if $g_{c_{22}}$ is chosen as

$$g_{c_{22}} = \frac{g_1}{g_1^*} g_{u_d} \quad (24)$$

where g_1^* is the minimum phase approximation of g_1. The transfer function g_1^* is constructed from g_1 by removing any time delays and reflecting all right-half-plane zeros across the imaginary axis (Morari and Zafiriou, 1989).

Equations 22–24 constitute the series representation of the habituating control system. The controller can be implemented using the parallel architecture by choosing $g_{c_{22}}$ as in Eq. 24 and the remaining controller transfer functions as,

$$g_{c_{11}} = -g_{c_1} g_{c_{21}} = \frac{g_{u_d} g_{y_d}}{(1-g_{y_d}) g_1^*} \quad (25)$$

$$g_{c_{12}} = (1-g_{c_{22}}) g_{c_1} = -\frac{g_2}{g_1^*} g_{u_d} \quad (26)$$

$$g_{c_{21}} = \frac{(g_1^* - g_1 g_{u_d})}{(1-g_{y_d}) g_1^* g_2} \quad (27)$$

where the expression for $g_{c_{21}}$ is obtained by substituting Eqs. 23 and 24 in Eq. 22.

The nominal closed-loop system is obtained by combining Eq. 1 with Eqs. 24–27:

$$\begin{bmatrix} y \\ u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} g_{y_d} & 0 & (1-g_{y_d}) g_3 \\ \dfrac{g_{u_d} g_{y_d}}{g_1^*} & -\dfrac{g_2}{g_1^*} g_{u_d} & -\dfrac{g_{u_d} g_{y_d}}{g_1^*} g_3 \\ \dfrac{(g_1^* - g_1 g_{u_d}) g_{y_d}}{g_1^* g_2} & \dfrac{g_1}{g_1^*} g_{u_d} & \dfrac{(g_1^* - g_1 g_{u_d}) g_{y_d}}{g_1^* g_2} g_3 \end{bmatrix} \times \begin{bmatrix} y_{sp} \\ u_{2_{sp}} \\ d \end{bmatrix}. \quad (28)$$

Asymptotic tracking of y_{sp} and $u_{2_{sp}}$ is achieved because the transfer functions y/d, u_2/y_{sp}, and u_2/d have zero steady-state gain. Because g_1 is assumed to be stable, nominal closed-loop stability is ensured for any stable transfer functions g_{y_d} and g_{u_d}. In order to remove the nonminimum-phase behavior from the output, $g_{c_{22}}$ is chosen as in Eq. 24 and the second control-objective is only approximately satisfied. Hence, the undesirable effects of the nonminimum phase transfer function g_1 have been removed from the output and "transferred" to the secondary input u_2. This behavior clearly demonstrates the advantage of habituating control as compared to SISO control techniques based on u_1 alone.

Because the series structure was employed to synthesize the controller for the nonminimum-phase case, a free controller transfer function is no longer available. This is a disadvantage of the series architecture since the additional transfer function ($g_{c_{21}}$ in the minimum-phase case) can be used to tune the responses of the two manipulated inputs to changes in y_{sp} and d. In the nonminimum-phase case, manipulated input moves can be adjusted via the transfer functions g_{y_d} and g_{u_d}. It is interesting to note that if g_1 is minimum phase and $g_{c_{21}}$ is chosen as in Eq. 18, then the closed-loop system in Eq. 28 is identical to the minimum-phase case in Eq. 17. Hence, the loss of a degree of freedom can be interpreted as the "price" associated with transferring the nonminimum-phase behavior to the secondary input.

Controller Saturation and Failure. When the achievable performance is limited by the dynamic effects of the primary input on the output, the habituating control approach will yield improved closed-loop performance with little increase in the long-term cost of control action. However, control system performance may also be limited by the steady-state gain between the primary input and controlled output. In this case, the primary input may become saturated or nearly saturated if the process is subjected to large setpoint changes and/or sustained disturbances. Hence, it may be desirable to allow changes in the setpoint of the secondary inputs in order to avoid primary input saturation. The new setpoints can be determined as follows:

$$u_{2_{sp}} = \frac{y_{sp} - k_1 u_{1_{sp}}}{k_2} \tag{29}$$

where $u_{1_{sp}}$ is the desired steady-state value for u_1, and k_1 and k_2 are the steady-state gains of g_1 and g_2, respectively.

An important advantage of the habituating control approach as compared to SISO control schemes is robustness to controller saturation and failure. If the actuator used by the secondary controller saturates or fails, asymptotic output tracking is still achieved by the primary controller. However, the closed-loop behavior will degrade and stability is not ensured. If the primary actuator saturates or fails, the secondary controller is still available to regulate the process. Asymptotic setpoint tracking is not achieved in this case because the secondary controller provides a compromise between the input and output tracking objectives. At steady state, the tracking errors are related as

$$\frac{y_{sp} - y}{u_{2_{sp}} - u_2} = -\frac{1}{k_2 k_{c_{21}}} \tag{30}$$

where $k_{c_{21}}$ is the steady-state gain of $g_{c_{21}}$. By contrast, asymptotic output tracking is completely compromised by actuator saturation and failure in SISO control techniques such as internal model control (Morari and Zafiriou, 1989).

Model-predictive control approach

The model-predictive controller design is based on a discrete-time process model of the form

$$y(z) = g_1(z)u_1(z) + g_2(z)u_2(z) + g_3(z)d(z). \tag{31}$$

Such models are usually obtained by discretizing a continuous-time model or by linear model identification. The transfer functions g_1 and g_2 may contain time delays (in addition to the sampling delay) and/or right-half-plane zeros as long as g_2 is "less" nonminimum phase than g_1. The three model transfer functions (g_1, g_2, g_3) are assumed to be stable, although the approach can be extended to the unstable case using the results of Rawlings and Muske (1993).

Controller Design. In the MPC approach, the control moves are generated by solving the following unconstrained optimization problem at each sampling instant (Clarke et al., 1987; Maurath et al., 1988; Garcia et al., 1989),

$$\begin{aligned}\min_{U(k)} \Phi = \sum_{i=1}^{P} \Big\{ & \gamma_i [y_{sp}(k+i) - \hat{y}(k+i|k)]^2 \\ & + \beta_{1i}[u_1(k+i-1|k) - u_1(k+i-2|k)]^2 \\ & + \beta_{2i}\left[u_{2_{sp}}(k+i-1) - u_2(k+i-1|k)\right]^2 \Big\}\end{aligned} \tag{32}$$

where P is the prediction horizon, $\hat{y}(k+i|k)$ is the predicted value of $y(k+i)$ based on information up to time k, $u_j(k+i|k)$ is the calculated value of $u_j(k+i)$ based on information up to time k, $\{\gamma_i\}$, $\{\beta_{1i}\}$, and $\{\beta_{2i}\}$ are weighting coefficients, and the vector $U(k)$ is defined in terms of the control horizon M as:

$$\begin{aligned}U(k) = [u_1(k|k), \ldots, u_1(k+M-1|k), u_2(k|k), \ldots, \\ u_2(k+M-1|k)]^T.\end{aligned} \tag{33}$$

In order to account for modeling errors, the predicted outputs are computed as

$$\hat{y}(k+i|k) = \tilde{y}(k+i|k) + (y(k) - \tilde{y}(k|k)) \tag{34}$$

where $\tilde{y}(k+i|k)$ is the model output at time $k+i$ based on information up to time k, and $y(k)$ is the process output at time k. Because the optimization in Eq. 32 involves only the first M control moves, the future model outputs are computed by setting:

$$u_j(k+i|k) = u_j(k+M-1|k) \quad \forall i \geq M, \quad j \in [1,2]. \tag{35}$$

A feedback control law is obtained by employing a receding horizon control strategy. Only the first calculated inputs are injected into the plant as $u_1(k) = u_1(k|k)$ and $u_2(k) = u_2(k|k)$, and the problem is then resolved at the next sampling instant.

Note that the objective function Φ in Eq. 32 is a modified version of the quadratic objective function employed in conventional SISO MPC control schemes (Prett and Garcia, 1988; Garcia et al., 1989). The habituating control objective function includes a penalty on the difference between the secondary input and its setpoint rather than a penalty on the secondary input's rate of change. This formulation enables the MPC controller to achieve asymptotic setpoint tracking if the closed-loop system is stable and the inputs are not saturated:

$$\lim_{k \to \infty} \{y_{sp}(k) - y(k)\} = 0$$

$$\lim_{k \to \infty} \{u_{2_{sp}}(k) - u_2(k)\} = 0 \qquad (36)$$

It is important to note that similar MPC control schemes for nonsquare systems are available from such MPC software vendors as Setpoint, Icotron, and Dynamic Matrix Control Corporation. However, differences in the dynamic effects and costs of the manipulated inputs are not explicitly considered.

The prediction horizon P, control horizon M, and weighting coefficients $\{\gamma_i\}$, $\{\beta_{1i}\}$, and $\{\beta_{2i}\}$ are the controller tuning parameters. In order to ensure nominal closed-loop stability for all values of the tuning parameters, P can be infinite (Bitmead et al., 1990) or a final state constraint can be enforced (Rawlings and Muske, 1993). The weighting coefficients can be chosen to reflect the relative values of the input and the output variables. If either input becomes saturated, the MPC controller will provide the minimum cost solution subject to that constraint. Asymptotic output tracking can be achieved even in the event of secondary input saturation. Conversely, if the primary input saturates, a compromise between the output and secondary input tracking objectives is obtained. Assuming that the weighting coefficients are independent of time, the steady-state tracking errors are related as

$$\frac{y_{sp}(k) - y(k)}{u_{2_{sp}}(k) - u_2(k)} = -\frac{\beta_2}{\gamma k_2}. \qquad (37)$$

Comparison with the Direct Synthesis Approach. Depending on the nature of the habituating control problem, either the direct synthesis approach or the MPC strategy may be more appropriate. Direct synthesis is preferred for high-performance, single-output loops because the effects of the controller tuning parameters on closed-loop performance are much more transparent; by contrast, the first three control objectives listed previously are not easily achieved with MPC. Additionally, the direct synthesis strategy requires less computation than MPC. However, MPC is a superior technique for constrained and/or MIMO processes; it also offers a unified controller design methodology for minimum-phase and nonminimum-phase processes.

Simulation Studies

The habituating control strategies developed in the preceding section are evaluated via simulation for three linear systems. A SISO controller is designed for each system using the primary manipulated input, and its performance is compared to that of a habituating controller that employs the primary and secondary inputs. In each case, the dynamic effect of the secondary input on the output is superior to that of the primary input, and the cost associated with manipulating the secondary input is greater than that associated with manipulating the primary input. The transfer function g_2 between the secondary input and controlled output is stable and minimum phase in each example, while the stable transfer function g_1 between the primary input and controlled output has the following characteristics:

- Example 1: g_1 has a large time constant as compared to g_2.
- Example 2: g_1 has a right-half-plane zero.
- Example 3: g_1 has a time delay.

Example 1

The first process model is

$$y(s) = \frac{1}{5s+1}u_1(s) + \frac{1}{2s+1}u_2(s) + \frac{1}{s+1}d(s) \qquad (38)$$

Note that the time constant in g_1 is larger than the time constant in g_2.

Direct Synthesis Approach. An internal model controller (Morari and Zafiriou, 1989) with a first-order filter was designed for Eq. 38 using only u_1. The time constant of the filter was chosen as $\lambda = 0.5$, and an additional setpoint filter with the same time constant was also employed to ensure smooth control moves for setpoint changes. Because g_1 is stable and minimum phase, the habituating controller was designed using the direct synthesis approach as in Eqs. 15 and 16 with

$$g_{y_d}(s) = \frac{1}{\epsilon_y s + 1}; \quad g_{u_d}(s) = \frac{1}{\epsilon_u s + 1}. \qquad (39)$$

The transfer functions were tuned with $\epsilon_y = 0.5$ and $\epsilon_u = 1$, and the controller transfer function $g_{c_{21}}$ was chosen to be a gain $k_{c_{21}} = 4$. As in the internal-model-control (IMC) approach, an additional setpoint filter with a time constant of 0.5 was also used.

Setpoint responses for IMC controller (dashed line) and the habituating controller (solid line) are shown in Figure 5.

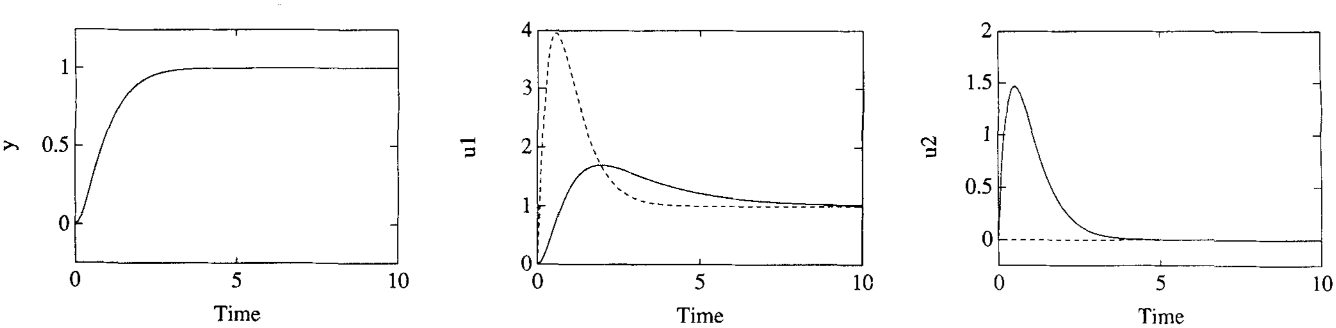

Figure 5. Direct synthesis and IMC control for an output setpoint change (Example 1).

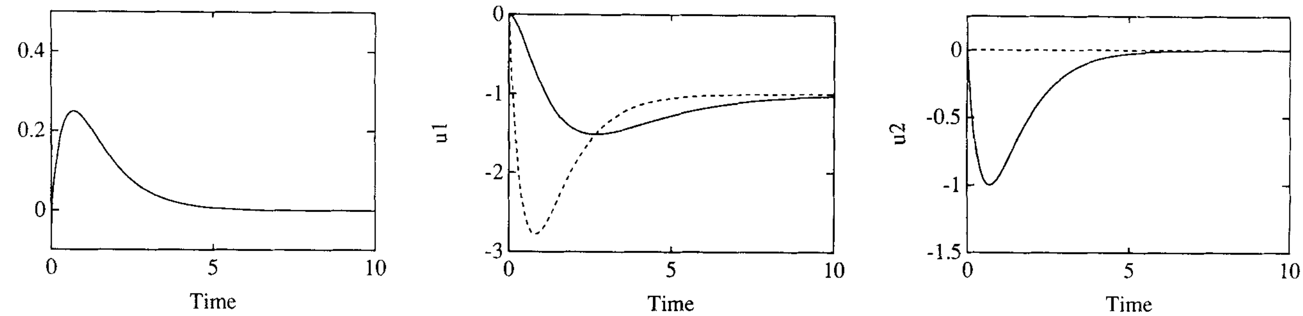

Figure 6. Direct synthesis and IMC control for an unmeasured disturbance (Example 1).

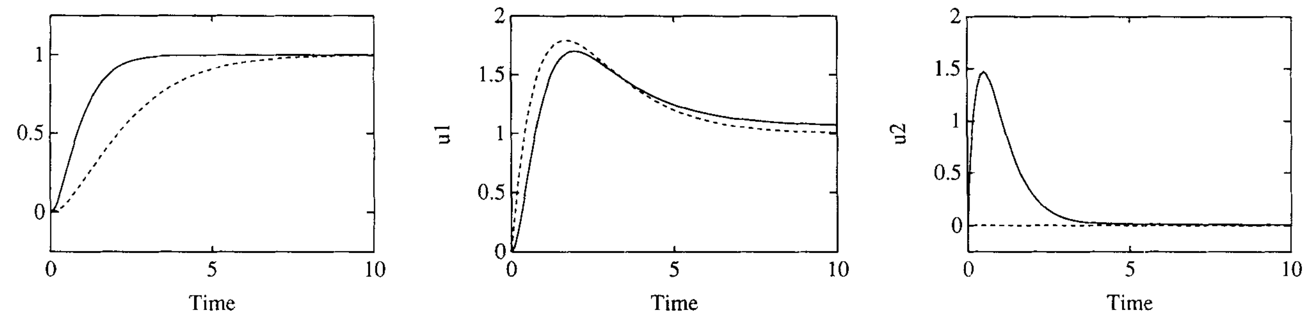

Figure 7. Direct synthesis and retuned IMC control for an output setpoint change (Example 1).

Identical output trajectories are obtained because the two controllers are tuned with the same time constants ($\lambda = \epsilon_y = 0.5$). However, the habituating controller requires significantly less aggressive control moves in the primary input than does IMC. The more conservative u_1 moves generated by the habituating controller are attributable to the use of the secondary input u_2 during the initial transient. Once u_1 begins to affect the output, u_2 returns to its setpoint $u_{2_{sp}} = 0$. The amount of u_2 control action expended can be adjusted with the controller gain $k_{c_{21}}$. For $k_{c_{21}} > 4$, the u_2 moves become too aggressive and an "inverse response" in u_1 occurs due to the presence of a right-half-plane zero in the u_1/y_{sp} transfer function in Eq. 17. The regulatory performance of the two controllers for a unit step change in the unmeasured disturbance d is shown in Figure 6. As before, identical output trajectories are obtained, but the IMC controller requires much more primary control action than the habituating controller.

Figures 5 and 6 demonstrate that habituating control can yield superior performance when input constraints are present. If the inputs are constrained as $-2 \leq u_1, u_2 \leq 2$, then the IMC controller must be detuned with $\epsilon_y = 1.25$ in order to avoid primary input saturation. Under these conditions, the setpoint responses in Figure 7 are obtained. The response of the habituating controller is identical to that in Figure 5 because controller retuning is not required to avoid u_1 saturation. Conversely, a very sluggish setpoint response is obtained with the IMC controller. Although not shown, the habituating controller also yields improved performance when the process model contains errors in the time constants.

Model-Predictive Control Approach. The example in Eq. 38 is also used to compare MPC-based habituating control and conventional MPC utilizing only the primary input u_1. A step response model with 80 coefficients was obtained by sampling the continuous time model with a period of 0.25. Both controllers have the form in Eq. 32 with a prediction horizon $P = 40$ and control horizon $M = 5$. For simplicity, the weighting coefficients were independent of time. The weighting co-

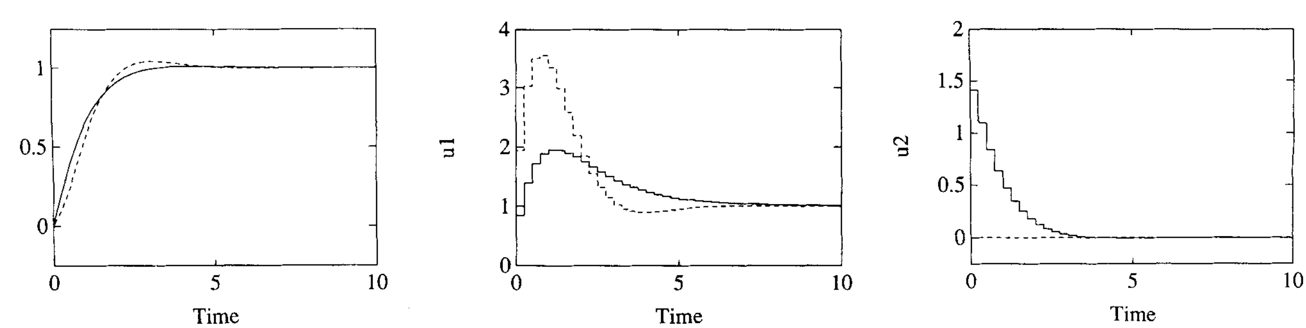

Figure 8. Habituating and SISO MPC for an output setpoint change (Example 1).

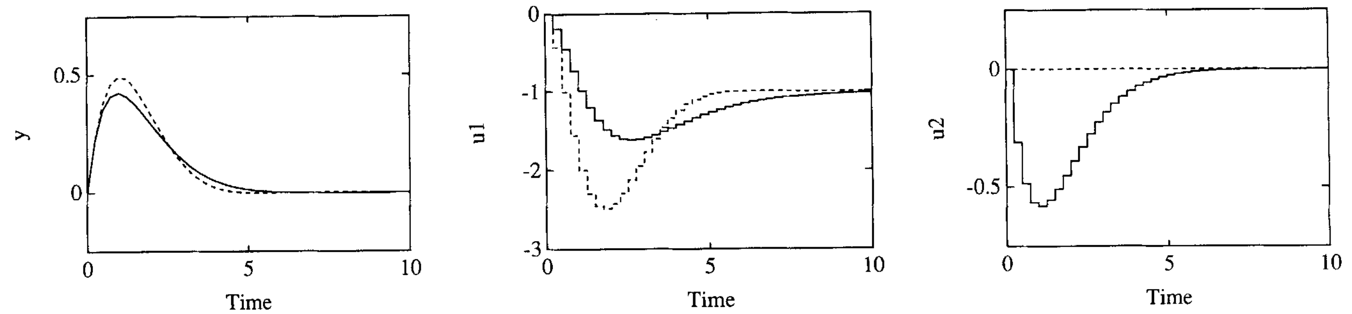

Figure 9. Habituating and SISO MPC for an unmeasured disturbance (Example 1).

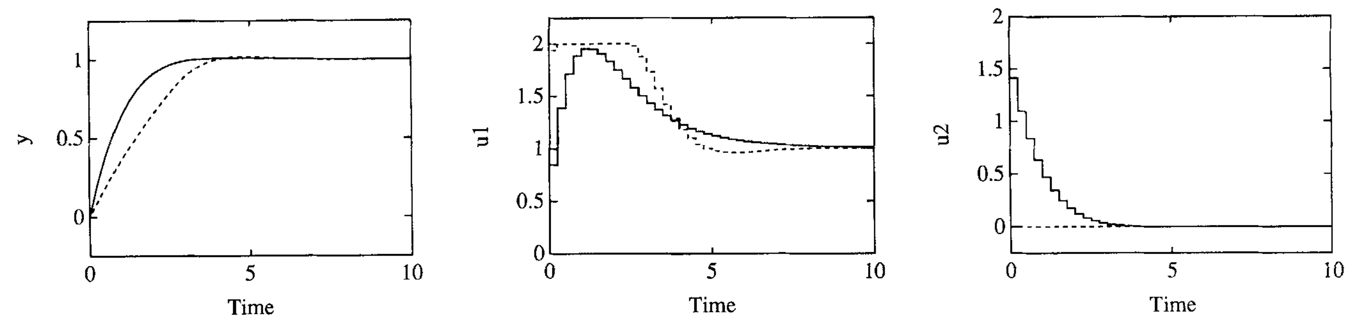

Figure 10. Constrained habituating and SISO MPC for an output setpoint change (Example 1).

efficients were chosen as $\gamma = 1$, $\beta_1 = 0.5$, and $\beta_2 = \infty$ in the SISO MPC approach in order to eliminate u_2 from the problem. In the habituating control formulation, the controller is tuned with $\gamma = 1$, $\beta_1 = 0.75$, and $\beta_2 = 0.5$. Setpoint responses for the conventional (dashed line) and habituating (solid line) MPC controllers are shown in Figure 8. The output trajectories are very similar, but as expected the primary control moves generated by the SISO controller are large compared to those of the habituating controller. The less aggressive primary control action of the habituating controller is due to the judicious use of u_2.

The performance of the two controllers for a unit step change in the unmeasured disturbance d is shown in Figure 9. The output responses are similar, but the habituating controller makes more conservative u_1 moves. The performance of the two MPC techniques when the inputs are constrained as $-2 \leq u_1, u_2 \leq 2$ is shown in Figure 10. The SISO controller is very sluggish because u_1 is saturated at its upper bound during the initial portion of the response. Conversely, the habituating controller remains unconstrained and therefore yields the same response as in Figure 8. Although not shown, the habituating controller also provides superior setpoint tracking and disturbance rejection when there are modeling errors in the time constants.

Example 2

The second process model is

$$y(s) = \frac{-2s+1}{(2s+1)^2} u_1(s) + \frac{1}{2s+1} u_2(s) + \frac{1}{s+1} d(s). \quad (40)$$

In this case, the transfer function g_1 contains a right-half-plane zero that limits the performance achievable with u_1

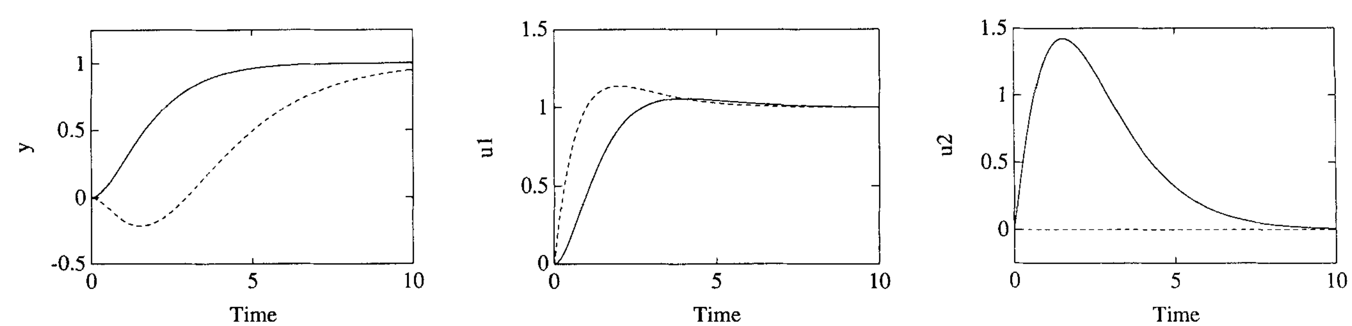

Figure 11. Direct synthesis and IMC control for an output setpoint change (Example 2).

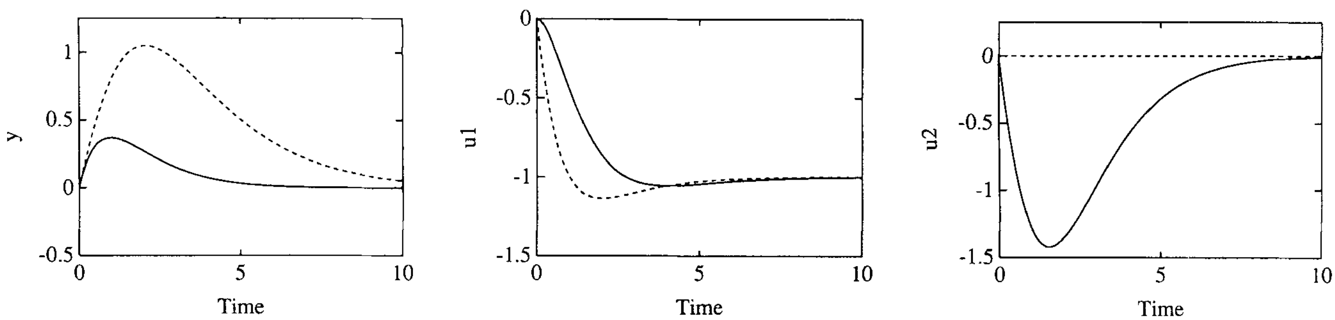

Figure 12. Direct synthesis and IMC control for an unmeasured disturbance (Example 2).

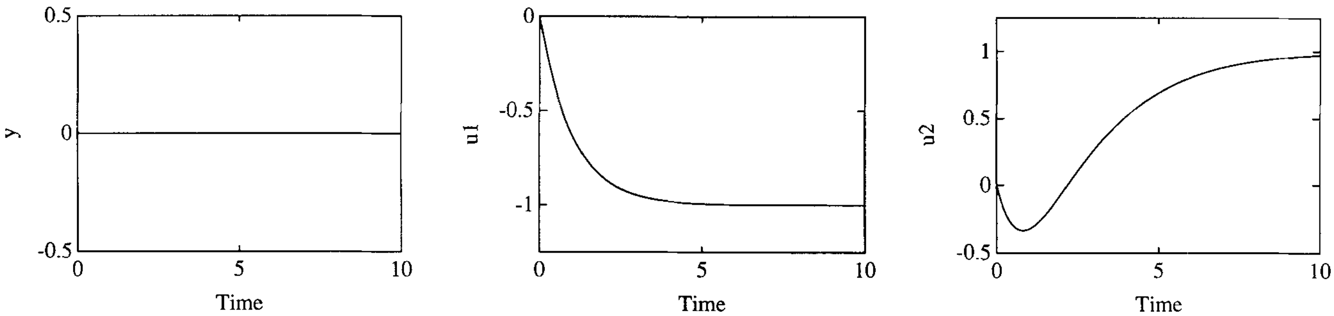

Figure 13. Direct synthesis control for an input setpoint change (Example 2).

alone. An IMC controller and a habituating controller based on direct synthesis are compared. In the IMC design, a first-order filter with time constant $\lambda = 1$ and an additional setpoint filter with the same time constant are employed. The habituating controller is designed as in Eqs. 24–27 because g_1 contains a nonminimum-phase element. The minimum-phase approximation of g_1 employed is

$$g_1^*(s) = \frac{1}{2s+1}. \tag{41}$$

The transfer functions g_{y_d} and g_{u_d} are chosen as in Eq. 39 and tuned with $\epsilon_y = \epsilon_u = 1$. An additional setpoint filter with the same time constant is also employed.

Setpoint responses for the IMC controller (dashed line) and habituating controller (solid line) are shown in Figure 11. By using the secondary input u_2, the habituating controller yields excellent performance without an inverse response in the output: the primary control moves are reasonable, and the secondary input returns to its setpoint $u_{2_{sp}} = 0$ once the setpoint change is accomplished. By contrast, the IMC controller produces very sluggish setpoint tracking with an inverse response. Faster setpoint tracking can be obtained by reducing λ, but this results in a more pronounced inverse response and larger control moves. Figure 12 shows the closed-loop responses of the two controllers for a unit step change in the unmeasured disturbance d. The habituating controller provides vastly superior performance with reasonable control moves; by contrast, the response of the IMC controller is very sluggish and cannot be improved by reducing λ.

As discussed previously, changes in the secondary input setpoint $u_{2_{sp}}$ may be desirable if operating conditions are changed. The performance of the habituating controller for a step change in $u_{2_{sp}}$ is shown in Figure 13. Note that u_2 ex-

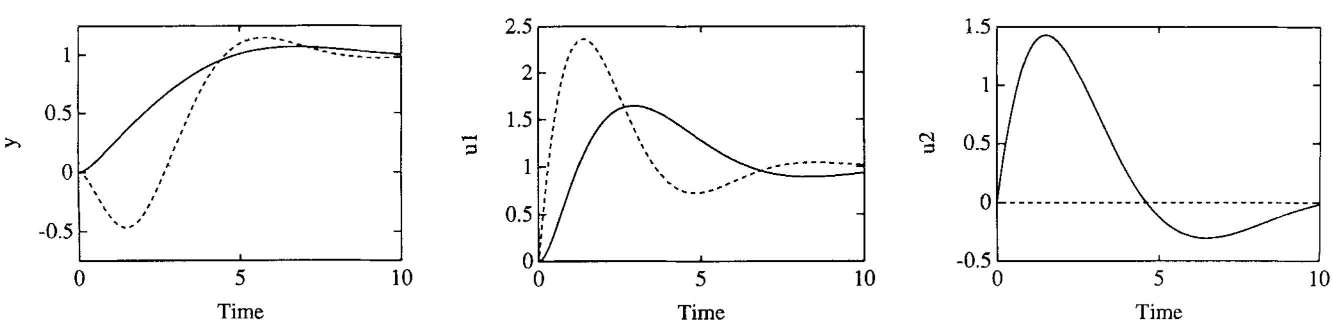

Figure 14. Robustness of direct synthesis and IMC control for an output setpoint change (Example 2).

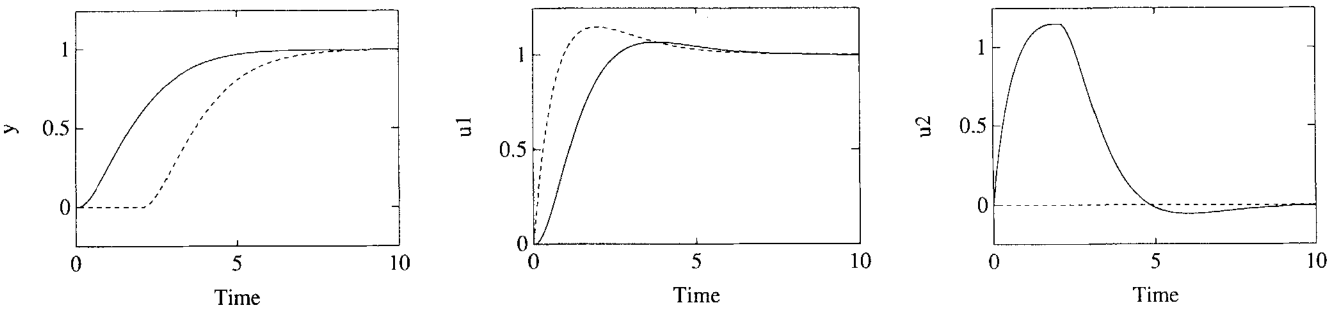

Figure 15. Direct synthesis and IMC control for an output setpoint change (Example 3).

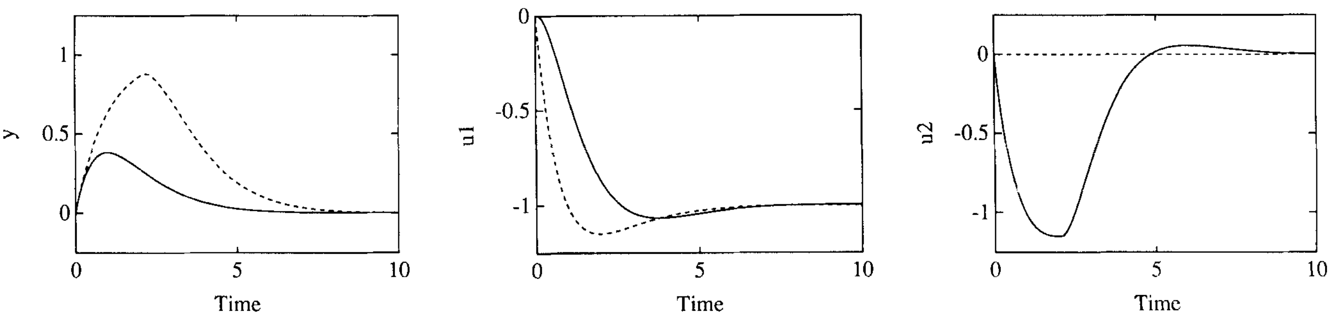

Figure 16. Direct synthesis and IMC control for an unmeasured disturbance (Example 3).

hibits an inverse response. Hence, the deleterious effects of the nonminimum-phase element have been transferred to the $u_{2_{sp}}$ response, but this is usually less important than the y_{sp} response. Figure 13 demonstrates that the output is decoupled from $u_{2_{sp}}$, and that the setpoint change is accomplished with reasonable u_1 control moves. Shown in Figure 14 is the setpoint tracking performance of the two controllers when the right-half-plane zero in model transfer function g_1 is assumed to be located at -1 instead of -0.5 as in Eq. 40. The habituating controller yields superior performance and requires less aggressive control moves in the primary input as compared to the IMC controller. However, the control moves of the direct habituating controller are slightly oscillatory as compared to the nominal case in Figure 11.

Example 3

In the final example, the transfer function g_1 has a time delay

$$y(s) = \frac{e^{-2s}}{2s+1}u_1(s) + \frac{1}{2s+1}u_2(s) + \frac{1}{s+1}d(s). \tag{42}$$

An IMC controller using only u_1 and a habituating controller based on direct synthesis are compared. A first-order filter with time constant $\lambda = 1$ is used in the IMC design. Due to the nonminimum-phase element in g_1, the habituating controller is designed as in Eqs. 24–27 and tuned with $\epsilon_y = \epsilon_u = 1$. An additional setpoint filter with time constant equal to 1 is employed in both approaches. It is important to note that the IMC design approach yields a Smith Predictor (Morari and Zafiriou, 1989), while prediction is not required in the habituating control scheme. Setpoint responses for the IMC controller (dashed line) and the habituating controller (solid line) are shown in Figure 15. The habituating controller is able to track the setpoint change without delay, while there is an unavoidable time delay of 2 time units in the IMC response.

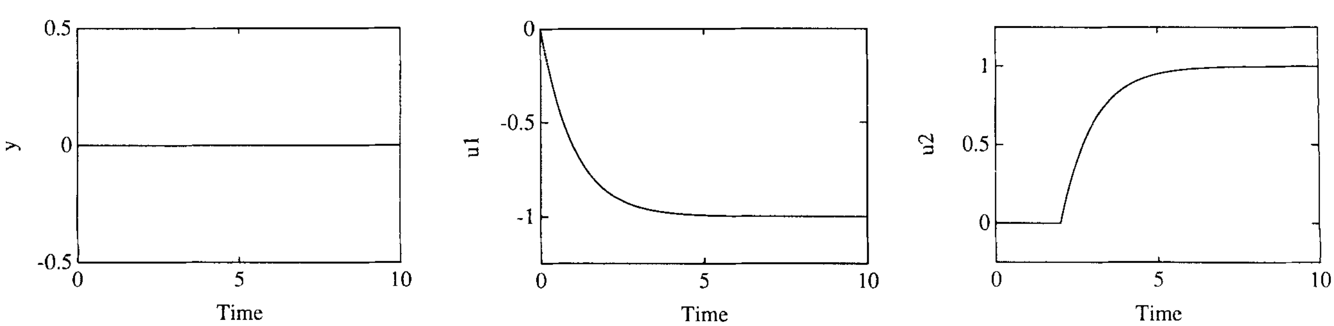

Figure 17. Direct synthesis control for an input setpoint change (Example 3).

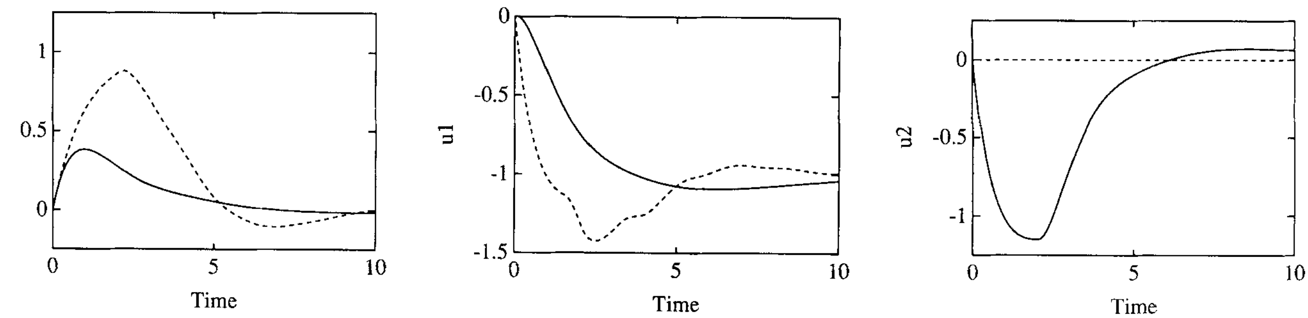

Figure 18. Robustness of direct synthesis and IMC control for an unmeasured disturbance (Example 3).

Closed-loop responses for a unit step change in the unmeasured disturbance d are shown in Figure 16. Because of the time delay between u_1 and y, the IMC response is very sluggish with large output tracking errors. By contrast, the habituating controller yields an excellent output response with reasonable control moves by employing u_2 during the initial transient. In Figure 17, the performance of the habituating controller for a step change in the secondary input setpoint $u_{2_{sp}}$ is shown. Note the effects of the time delay in the u_2 response. The output is decoupled from $u_{2_{sp}}$ and the transition is accomplished with reasonable u_1 moves. Shown in Figure 18 is the regulatory performance of the two approaches when the time delay of the model transfer function g_1 is underestimated as 1.5 time units instead of 2 time units as in Eq. 42. The system is subjected to a unit step change in d. The habituating controller provides a superior response with smoother and less aggressive u_1 moves. In fact, the habituating controller response is similar to the perfect model case shown in Figure 16.

Summary and Conclusions

Habituating control strategies for process control applications have been "reversed engineered" from a biological control system. The habituating control system consists of primary and secondary manipulated inputs that differ in terms of their relative costs and dynamic effects on the output. The primary inputs are employed primarily for steady-state control, while the secondary inputs are used only during transients. The habituating control objectives and architecture were abstracted from the robust, high-performance control system responsible for mammalian blood pressure regulation. Several process control examples, including a heat exchanger and polymerization reactor, were discussed to indicate the wide range of potential applications of the habituating control approach.

Two basic controller design strategies were presented for linear processes with two manipulated inputs and one controlled output. In the *direct synthesis approach*, the desired closed-loop behavior is specified and the controller that meets the objectives is synthesized directly. As compared to alternative control techniques proposed for multiple-input, single-output systems, the habituating control strategy is straightforward and systematic. The *model predictive control* technique is based on a simple, but important, modification of the standard quadratic objective function employed in existing techniques. Simulation results were presented for process models that exhibit minimum-phase and nonminimum-phase behavior. The results demonstrate the superior performance that can be achieved with habituating control as compared to single-input, single-output control techniques.

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