Integrated Product and Process Control of Single-Input-Single-Output Systems

Jie Xiao and Yinlun Huang
Dept. of Chemical Engineering and Materials Science, Wayne State University, Detroit, MI 48202

Yu Qian
School of Chemical and Energy Engineering, South China University of Technology, Guangzhou, China

Helen H. Lou
Dept. of Chemical Engineering, Lamar University, Beaumont, TX 77710

DOI 10.1002/aic.11120

In many chemical and allied manufacturing systems, product quality is controlled based on postprocess quality inspection on sampled final products. Statistical analysis of the identified quality problems is then utilized to improve process operation, and thus the quality of succeeding products. Although this type of reactive *quality control (QC) is necessary, it is not only inefficient because it "waits for" the occurrence of product quality problems, but also ineffective due to usually a significant time lag from problem identification, through solution derivation, to action taking. Furthermore, the derived solutions for problem solving are mostly heuristic in nature. This paper introduces a* proactive *product QC approach, which is established based on the concept of integrated product and process (IPP) control. Aiming at simultaneous dynamic control of process operation and product manufacturing, this approach ensures* all-time *systematic control of both process performance and product quality. From the view point of both process control and product control, it is shown that IPP control can be realized by resorting to a well known scheme, cascade control. The IPP control problem for Single-Input-Single-Output systems can be formulated rigorously, and the control laws can be identified readily. A synthesized IPP control system can effectively reject disturbances on the process and the product, and have excellent set-point tracking capability, regardless of the type of interaction between the process and the product. The efficacy and attractiveness of the IPP control system design methodology are demonstrated through two types of case studies.*

AIChE J, 53: 891–901, 2007

Keywords: product quality control, process control, integrated product and process engineering

Introduction

In many chemical and allied manufacturing systems, product quality control (QC) has been traditionally practiced through postprocess quality inspection.[1] The identified quality problems are usually statistically analyzed and solution(s) may be derived. Actions will then be taken by process engineers to improve process operation with a hope that the same types of quality problems will not be repeated in succeeding production. The inspection-based QC is a reactive approach, which has several major deficiencies. First, it is to "wait for" quality problem(s) to occur, but not to prevent them in the first place. Second, it is usually inefficient in problem fixing during

---

Y. Huang is also affiliated with School of Chemical and Energy Engineering, South China University of Technology, Guangzhou, China.

Correspondence concerning this article should be addressed to Prof. Yinlun Huang at yhuang@wayne.edu.

production because of a significant time lag from problem identification to information feedback for process control adjustment. Note that in a fast manufacturing system, once a quality problem is identified in a specific product, the same type of problems will be repeated in a large number of products in a short time period. Third, but not the last, the solutions for process improvement are usually heuristic based and likely inconsistent. Thus, problems solving could be ineffective.

The inspection-based QC approach is surely necessary in manufacturing, as it serves as a final quality guard. Nevertheless, this is not sufficient, particularly because of increased pressure on cost reduction and quality assurance. On the other hand, modern QC means "on-aim" control, where variability in either direction from a specification should be avoided.[2] This demands product QC to be *proactive* rather than *reactive*, which should focus on quality assurance starting from the earliest stage of product manufacturing. Wu et al. indicated that a new generation of QC should be based on process control, but no information was provided for establishment of correlation between process control and QC.[3] Yabuki and MacGregor introduced a practical approach called midcourse correction to control the final product quality for a semi-batch reactor.[4] By their approach, on-line process measurements and off-line product quality related evaluation of samples need be used to predict final product quality. If the prediction does not fall into a quality permissible region, then correction on process will be suggested. While product quality issues are taken into account, the approach is incapable of realizing real-time closed-loop QC. Moreover, how to determine optimal sampling moments is yet to be developed.[5]

Lou and Huang introduced a process-focused proactive QC approach, with a key requirement of dynamic modeling of both process and product.[6,7] Most recently, Xiao et al. extended the approach by adding quality-bearing off-line process optimization to process feedback control, with applications to automotive coating curing.[8,9] The approach permits adjustment of process operational settings when a need for quality improvement is justified, and thus it can be regarded as hierarchical process control toward proactive QC that is general for any manufacturing systems. However, the optimization does not take into account expected/unexpected quality-related disturbances, and thus product quality may be threatened under certain circumstances. Besides, off-line optimization is not sufficient for truly all-time proactive QC.

It becomes clear that "one-time" quality inspection *after* manufacturing is ineffective, and process optimization or midcourse correction is insufficient. A truly proactive QC needs to be realized through "all-time" QC *during* manufacturing; it can be referred to *product dynamic control*, as against conventional process dynamic control.

In this study, we will show that a precondition of product dynamic control is realization of process control. This leads to an introduction of a concept of integrated product and process (IPP) control. It will be then shown that a cascade-control-based IPP control scheme is general and applicable to the problem where the process and the product have either unidirectional or bidirectional interaction. IPP control of Single-Input-Single-Output (SISO) systems is the focus of this work. Assuming the process and the product behaviors in the IPP system can be approximated by linear models, a general controller synthesis method is introduced. To demonstrate the efficacy of the proposed method, two problems are studied in detail, where the designed IPP controllers can be used very effectively to assure product quality when both the process and the product experience disturbances in different ways; meanwhile, process efficiency can also be assured.

All-Time Product Quality Control

As stated, a precondition of product dynamic control is realization of process control. Process control, by all means, is to control a process so that it can demonstrate satisfactory dynamic performance, which is reflected by the value of the controlled variable.[10] It is expected that the controlled variable track the set-point satisfactorily under the condition that the process may experience disturbances (i.e., for regulatory control) or set-point change (i.e., for servo control).[11]

There can be many factors for process set-point determination, such as those related to operation feasibility (e.g., reaction temperature), process efficiency (e.g., energy and material efficiency), process safety (e.g., vassal pressure), and waste reduction (e.g., effluent stream composition). But in any case, a premise of the selection of process set-point value is that the *final product quality* should be at least satisfactory, because an ultimate goal of process operation is to manufacture a desired product.

Many practical examples show that process control alone can assure product quality. In distillation column control, for example, if process controlled variables (e.g., reflux ratio, column pressure, and liquid level) are well controlled, then product quality (e.g., the component compositions of the distillate and bottom streams) can be guaranteed. In an ingot heating furnace of a steel works, if process controlled variables (i.e., the wall temperatures in different locations of a heating furnace) are well controlled, then product quality (e.g., the temperature uniformity throughout each ingot in different locations) can also be guaranteed. Note that in the first case, the product quality can be measured on site, but this is not the case for the second one because of measurement difficulty and cost.

There are many other cases where process control itself cannot assure product quality. Even if the set-point for a process controlled variable is optimally selected and the process is perfectly controlled for set-point tracking, product quality may still not be under control if a disturbance is exerted to the product or if the process experiences severe instability. Since process control is incapable of controlling product quality directly, product quality could be under threat in many ways. Automotive coating curing process is an example. In polymeric material application on vehicles, each layer of wet coating is baked in an oven that is usually divided into several heating zones. In operation, only the wall temperature and the air temperature and velocity in each zone can be measured and controlled. The coating quality variables, i.e., the coating film thickness, crosslinking conversion, as well as solvent removal, are all impossible to be measured online.[6–8] The only measurement on the product (usually less than 5% of products can be practically sampled) is the dry film thickness *after* the curing is completed. Process control concerns wall and air temperatures as well as air velocities in the oven. The product quality is essentially under no control *during its manufactur-*

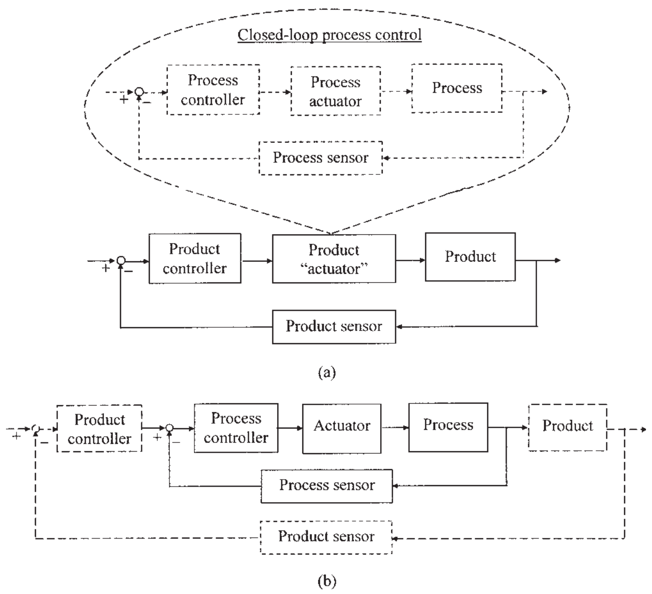


Figure 1. Control scheme for proactive product control: (a) product control realization via process control and (b) extension of process control to product control.

ing steps.[8] The films (i.e., the product) in baking may experience some disturbances in the form of, for example, surface contamination (such as oil drop from the oven ceiling to the film surface). This type of disturbances does affect product quality but not process control. The IPP methodology developed in this work is specifically for this class of product manufacturing processes. A successful development of this type of methodology should help advance usual, "reactive" industrial practice of process control plus a postprocess inspection based QC to "proactive" practice of simultaneous real-time control of both process performance and product quality.

From the control point of view, product QC should be realizable through closed-loop feedback control. As shown in Figure 1a, a product controller provides control signal to the product "actuator" that must be process related, as it is the process where the product can be manufactured. Consequently, product dynamic control must be realized together with the dynamic control of the process (see the closed-loop process control block diagram in the dotted area in Figure 1a). This reasoning leads to the scheme, which is the same as the conventional cascade control scheme. Note that process controlled variables (from the inner loop) are essentially the "manipulated" product variables (of the outer loop) that determine product manufacturing behavior.

As discussed earlier, since process control alone may not guarantee final product quality and product QC cannot be realized without process control, IPP control is a local path to achieve simultaneously "needed" process performance and "on-aim" product quality.

The cascade-control-based IPP control scheme can also be derived in another way. As stated, traditional process feedback control has only one focus, i.e., on controlling process controlled variable to achieve a satisfactory performance; in process control system synthesis, product quality is not directly considered. In reality, the controlled variable of the process directly affects product quality (see, Figure 1b). To control product quality as well, the product quality dynamic information should also be collected and utilized to realize closed-loop product control (see the dotted lines in Figure 1b). Again, this is a cascade control scheme for IPP control for "all-time" "on-aim" QC.

In summary, a generalized scheme for IPP control is cascade control scheme, with the inner loop for process control, and the outer loop for product control.

Integrated Product and Process Control

In this work, linear SISO process-product systems are studied. The IPP control scheme for such systems is shown in Figure 2 where the two controllers, i.e., the process controller, G_c^c, and the product controller, G_c^d, are grouped together; the grouped one can be named the IPP controller. The IPP controller has three types of inputs: the set point for product quality, Y_{sp}^d, the process performance feedback, Y_m^c, and the product performance feedback, Y_m^d. The product controller, G_c^d, provides a regulated set-point of the process controller, G_c^c. The output of the IPP controller is to control the process through adjusting the actuator, G_a^c. Note that Y^c is the process controlled variable, Y^d is the product controlled variable, and U is the manipulated variable.

The overall transfer function of the IPP control can be readily obtained below:

$$\frac{Y^c}{Y_{sp}^c} = \frac{G_c^c G_a^c G_p^c}{1 + G_c^c G_a^c G_p^c G_m^c} \tag{1}$$

$$\frac{Y^d}{Y_{sp}^d} = \frac{G_c^d \left(\frac{Y^c}{Y_{sp}^c}\right) G_p^d}{1 + G_c^d \left(\frac{Y^c}{Y_{sp}^c}\right) G_p^d G_m^d} \tag{2}$$

Let

$$\frac{Y^c(s)}{Y_{sp}^c(s)} = G^{c,D} \tag{3}$$

$$\frac{Y^d(s)}{Y_{sp}^d(s)} = G^{d,D} \tag{4}$$

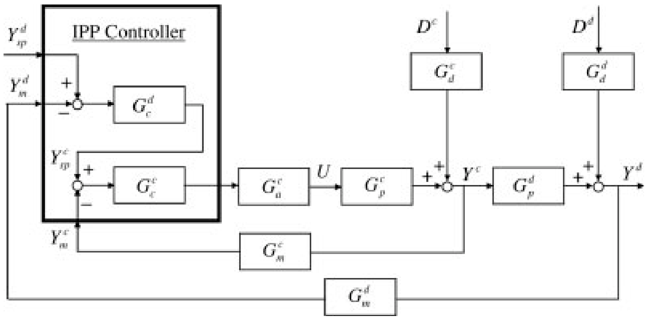


Figure 2. IPP control scheme.

the general transfer function of the process controller of the IPP controller can be derived as,

$$G_c^c = \frac{G^{c,D}}{G_a^c G_p^c (1 - G^{c,D} G_m^c)} \tag{5}$$

and the general transfer function of the product controller of the IPP controller is:

$$G_c^d = \frac{G^{d,D}}{G^{c,D} G_p^d (1 - G^{d,D} G_m^d)} \tag{6}$$

Controller design for desired first-order-plus-time-delay closed-loop response

There could be a number of ways to design an IPP controller. A target-oriented approach for determining the type of control laws as well as controller parameters in process controller design is adopted here.[12,13] This approach can be used to design a product controller as well. The target here is the desired closed-loop dynamic performance of both the process and the product. The desired dynamic performance can be expressed by transfer functions. For instance, the desired transfer functions for both the process and the product are assumed to have the following first order form with time delay.[13]

$$G^{c,D} = \frac{e^{-\theta^c s}}{\tau^{c,D} s + 1} \tag{7}$$

$$G^{d,D} = \frac{e^{-(\theta^d + \theta^c)s}}{\tau^{d,D} s + 1} \tag{8}$$

where θ^c and θ^d are the time delay in the process model and in the product model, respectively; $\tau^{c,D}$ and $\tau^{d,D}$ are the desired closed-loop time constant of the process and the product, respectively.

Using the desired dynamic performance in Eqs. 7, 8, and for simplicity, assume that the transfer functions of the actuators and sensors (G_a^c, G_m^c, and G_m^d) are all equal to "1", the IPP controller can be designed as follows:

$$G_c^c = \frac{1}{G_p^c} \cdot \left(\frac{e^{-\theta^c s}}{\tau^{c,D} s + 1 - e^{-\theta^c s}} \right) \tag{9}$$

$$G_c^d = \frac{1}{G_p^d} \cdot \left(\frac{e^{-\theta^d s}(\tau^{c,D} s + 1)}{\tau^{d,D} s + 1 - e^{-(\theta^d + \theta^c)s}} \right) \tag{10}$$

The time-delay terms in the denominators of Eqs. 9, 10 can be approximated by truncated Taylor series expansions, i.e.,

$$e^{-\theta^c s} = 1 - \theta^c s \tag{11}$$

$$e^{-(\theta^d + \theta^c)s} = 1 - (\theta^d + \theta^c)s \tag{12}$$

Substituting Eqs. 11, 12 into Eqs. 9, 10 and rearranging the resulting expressions gives:

$$G_c^c = \left(\frac{e^{-\theta^c s}}{G_p^c} \right) \left(\frac{1}{(\tau^{c,D} + \theta^c)s} \right) \tag{13}$$

$$G_c^d = \left(\frac{e^{-\theta^d s}}{G_p^d} \right) \left(\frac{\tau^{c,D}}{\tau^{d,D} + \theta^d + \theta^c} \right) \left(1 + \frac{1}{\tau^{c,D} s} \right) \tag{14}$$

Note that, with the IPP controller, the process and product outputs, y^c and y^d, will approach their respective set-points, ${y_{sp}}^c$ and ${y_{sp}}^d$, in the following ways:

$$y^c = \begin{cases} \left(1 - \exp\left(\frac{-(t-\theta^c)}{\tau^{c,D}}\right)\right) y_{sp}^c & t \geq \theta^c \\ 0 & 0 \leq t < \theta^c \end{cases} \tag{15}$$

$$y^d = \begin{cases} \left(1 - \exp\left(\frac{-(t-\theta^c-\theta^d)}{\tau^{d,D}}\right)\right) y_{sp}^d & t \geq \theta^c + \theta^d \\ 0 & 0 \leq t < \theta^c + \theta^d \end{cases} \tag{16}$$

Note that the IPP controller may have various forms of control laws, depending on the types of product and process systems of interest.

IPP controller design for the product and process system of first-order-plus-time-delay

If both the process and/or the product are of higher orders in modeling, they can be usually readily approximated by first-order-plus-time-delay transfer functions,[14] which are of the following structures:

$$G_p^c = \frac{K_p^c e^{-\theta^c s}}{\tau_p^c s + 1} \tag{17}$$

$$G_p^d = \frac{K_p^d e^{-\theta^d s}}{\tau_p^d s + 1} \tag{18}$$

In this case, substituting Eq. 17 into Eq. 13, using $\tau^{c,D}$ in Eq. 7, and then simplifying the resulting expression can yield,

$$G_c^c = \frac{\tau_p^c}{K_p^c(\tau^{c,D} + \theta^c)} \left(1 + \frac{1}{\tau_p^c s} \right) \tag{19}$$

Obviously, the process controller of the IPP controller is a PI controller; it can be written as,

$$G_c^c = K_P^c \left(1 + \frac{1}{\tau_I^c s} \right) \tag{20}$$

where the proportional and the integral parameters are:

$$K_P^c = \frac{\tau_P^c}{K_p^c(\tau^{c,D} + \theta^c)} \tag{21}$$

$$\tau_I^c = \tau_P^c \tag{22}$$

Also substituting Eq. 18 into Eq. 14 using $\tau^{d,D}$ in Eq. 8, then simplifying the expression gives,

$$G_c^d = \left(\frac{\tau_p^d + \tau^{c,D}}{K_p^d(\tau^{d,D} + \theta^c + \theta^d)} \right) \times \left(1 + \left(\frac{1}{\tau_p^d + \tau^{c,D}} \right) \frac{1}{s} + \left(\frac{\tau^{c,D} \tau_p^d}{\tau_p^d + \tau^{c,D}} \right) s \right) \tag{23}$$

Clearly, the product controller of the IPP controller is a PID controller; it can be written as,

$$G_{\mathrm{c}}^{\mathrm{d}} = K_{\mathrm{P}}^{\mathrm{d}}\left(1 + \frac{1}{\tau_{\mathrm{I}}^{\mathrm{d}} s} + \tau_{\mathrm{D}}^{\mathrm{d}} s\right) \tag{24}$$

where

$$K_{\mathrm{P}}^{\mathrm{d}} = \frac{\tau_{\mathrm{p}}^{\mathrm{d}} + \tau^{\mathrm{c,D}}}{K_{\mathrm{p}}^{\mathrm{d}}\left(\tau^{\mathrm{d,D}} + \theta^{\mathrm{c}} + \theta^{\mathrm{d}}\right)} \tag{25}$$

$$\tau_{\mathrm{I}}^{\mathrm{d}} = \tau_{\mathrm{p}}^{\mathrm{d}} + \tau^{\mathrm{c,D}} \tag{26}$$

$$\tau_{\mathrm{D}}^{\mathrm{d}} = \frac{\tau^{\mathrm{c,D}}\tau_{\mathrm{p}}^{\mathrm{d}}}{\tau_{\mathrm{p}}^{\mathrm{d}} + \tau^{\mathrm{c,D}}} \tag{27}$$

In this case, the IPP controller consists of a PID controller (for product control) and a PI controller (for process control) that are connected directly. All controller parameters can be systematically determined, if the desired closed-loop performance for both the process and the product can be expressed by first-order with time-delay transfer functions, and first-order-plus-time-delay models can satisfactorily describe the process and the product behaviors.

IPP controller design for the product and process system with bidirectional interactions

The controller design formulas in Eqs. 20–27 are for the process and product system with unidirectional interaction from the process to the product, which is shown in Figure 2. It is worth noting that some process and product system has bidirectional interactions, i.e., the product performance can affect the process performance as well. Some batch reactors can also be an example, where the reactor temperature (a process controlled variable) and the product quality (e.g., the product concentration) can affect each other dynamically. Under such circumstances, it can be shown that the proposed IPP controller design methodology described in the preceding section is still applicable.

Figure 3 shows a process and product control system where an IPP controller is used and an intrinsic interaction from the product to the process through the transfer function, $G_{\mathrm{d}}^{\mathrm{dc}}$, exists. With this additional interaction, the traditional process feedback control system may be incapable of achieving satisfactory process performance and product performance even under no direct process and product disturbances. Nevertheless, the IPP controller shown in Eqs. 13, 14 can be used to control this type of bidirectional interactive process and product system.

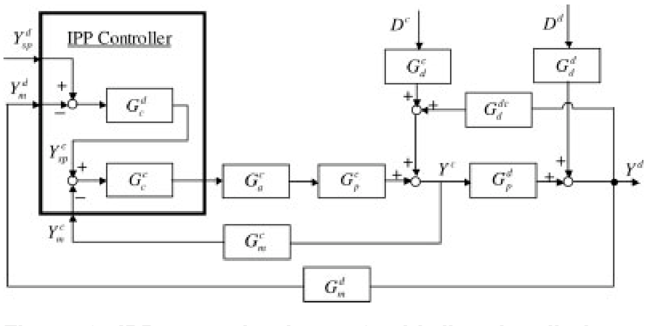


Figure 3. IPP control scheme for bi-directionally interactive process and product system.

Case Studies

The IPP control system design methodology is general and applicable to a variety of SISO process and product system control problems. Two case studies are illustrated in this section to demonstrate its applicability.

Case I: Unidirectional interactive process and product system

A simplified automotive polymeric coating system is studied in this case. In production, vehicle bodies, after one step of paint spray, are covered by a thin layer of polymeric film. They then travel one by one through the oven for film drying/curing. The oven is usually divided into a number of zones so that different heating mechanisms (i.e., radiation from the oven walls and hot air convection) can be applied under different conditions. In operation, the solvent contained in the wet film is removed by heat, film thickness and thus topology changes, and polymerization (i.e., crosslinking reaction) takes place within the film. Finally, cured coating with desired properties is developed on each vehicle surface as the final product. The detailed curing process description and system models can be found in Lou and Huang.[6]

The process and product control problem is shown in Figure 2. The original system is simplified as a SISO system, where the process controlled variable, y^{c}, is the automotive panel temperature (denoted as T), which is also the polymeric material temperature. The product controlled variable, y^{d}, is the crosslinking conversion (denoted as x). The manipulated variable, u, is the convection air temperature (denoted as T_{a}). To ensure a satisfactory coating quality, the final crosslinking conversion needs to reach a desired value (e.g., 90%).[6,9]

Panel heating can be readily modeled according to the energy conservation,[6] i.e.,

$$\rho_{\mathrm{m}} C_{\mathrm{p_m}} Z_{\mathrm{m}} \frac{\mathrm{d}T}{\mathrm{d}t} = h_v (T_{\mathrm{a}} - T) \tag{28}$$

where ρ_{m}, $C_{\mathrm{p_m}}$ and Z_{m} are density, heat capacity, and the thickness of the metal substrate, respectively; h_v is the heat transfer coefficient; T_{a} is the convection air temperature; T is the panel temperature. This gives a first-order process model, i.e.,

$$G_{\mathrm{p}}^{\mathrm{c}} = \frac{Y^{\mathrm{c}}}{U} = \frac{T(s)}{T_{\mathrm{a}}(s)} = \frac{K_{\mathrm{p}}^{\mathrm{c}}}{\tau_{\mathrm{p}}^{\mathrm{c}} s + 1} = \frac{3}{50s + 1} \tag{29}$$

A first-order reaction is used to characterize the main feature of the crosslinking reaction,[6,15] i.e.,

$$\frac{\mathrm{d}x}{\mathrm{d}t} = \zeta e^{-\mathrm{E_r}/\mathrm{RT}}(1 - x) \tag{30}$$

where x is the crosslinking conversion; E_{r} is the reaction activation energy; R is the gas constant; and ζ is the reaction frequency factor. The product behavior given by Eq. 30 can be approximately described by a first-order-plus-time-delay model, by which the product quality can be monitored:

$$G_{\mathrm{p}}^{\mathrm{d}} = \frac{Y^{\mathrm{d}}}{Y^{\mathrm{c}}} = \frac{x(s)}{T(s)} = \frac{K_{\mathrm{p}}^{\mathrm{d}} e^{-\theta^{\mathrm{d}} s}}{\tau_{\mathrm{p}}^{\mathrm{d}} s + 1} = \frac{e^{-10s}}{32(700s+1)} \tag{31}$$

The system experiences two types of disturbances, one on the process, and the other on the product. The process and product disturbances are described, respectively, by the following first-order models:

$$G_{\mathrm{d}}^{\mathrm{c}} = \frac{K_{\mathrm{d}}^{\mathrm{c}}}{\tau_{\mathrm{d}}^{\mathrm{c}} s + 1} = \frac{30}{120s+1} \tag{32}$$

$$G_{\mathrm{d}}^{\mathrm{d}} = \frac{K_{\mathrm{d}}^{\mathrm{d}}}{\tau_{\mathrm{d}}^{\mathrm{d}} s + 1} = \frac{1}{100s+1} \tag{33}$$

In this study, the desired closed-loop time constants for the process and the product, $\tau^{\mathrm{c,D}}$ and $\tau^{\mathrm{d,D}}$, are set to 5 and 15, respectively.

Process and Product Performance with Only Process Controller. The system is firstly studied using only a process controller (see the dashed block diagram in Figure 1a), which is the usual industrial practice in automotive polymeric coating manufacturing. Since the first-order-plus-time-delay closed-loop response is assumed, the general form for a process controller is given by Eq. 13. The process controller can be designed through substituting the process model (i.e., Eq. 29) into Eq. 13. In this case, θ^{c} equals to 0. This gives:

$$G_{\mathrm{c}}^{\mathrm{c}} = K_{\mathrm{P}}^{\mathrm{c}}\left(1 + \frac{1}{\tau_{\mathrm{I}}^{\mathrm{c}} s}\right) \tag{34}$$

where the controller parameters are:

$$K_{\mathrm{P}}^{\mathrm{c}} = \frac{\tau_{\mathrm{P}}^{\mathrm{c}}}{K_{\mathrm{p}}^{\mathrm{c}}\left(\tau^{\mathrm{c,D}} + \theta^{\mathrm{c}}\right)} = 3.33 \tag{35}$$

$$\tau_{\mathrm{I}}^{\mathrm{c}} = \tau_{\mathrm{p}}^{\mathrm{c}} = 50 \tag{36}$$

System Under Process Disturbance. Figure 4a depicts the process disturbance with the change from 0 to −12 at the 1030th s. As shown in Figure 4b, the process controlled variable (i.e., the panel temperature) is disturbed immediately when the disturbances enters, but with the process controller, moves towards the set-point quickly. Note that since the whole process operation lasts 1200 s, the process controlled variable does not return to the set-point at the end of the operation. The impact of this process performance on the product is shown in Figure 4c. The product quality has a problem at the end of the process operation, because the product quality variable, y^{d} (i.e., the crosslinking conversion, x), is below the lowest acceptable value (i.e., 90% conversion in this case).

System Under Both Process and Product Disturbances. If the system experiences both process disturbance and product disturbance, the product quality may face a more severe challenge. Figure 5a depicts a product disturbance occurring at the 500th s, with the change from 0 to −0.1, and a process disturbance (the same as the case earlier, i.e., occurring at the 1030th s, with the change from 0 to −12). In this case, the process performance is the same as that in the case earlier (see Figure 5b, which is the same as Figure 4b). Nevertheless, the product quality is affected starting at the 500th s (see, Figure 5c and its comparison with Figure 4c). Obviously, the use of a process controller alone is not acceptable for quality assurance.

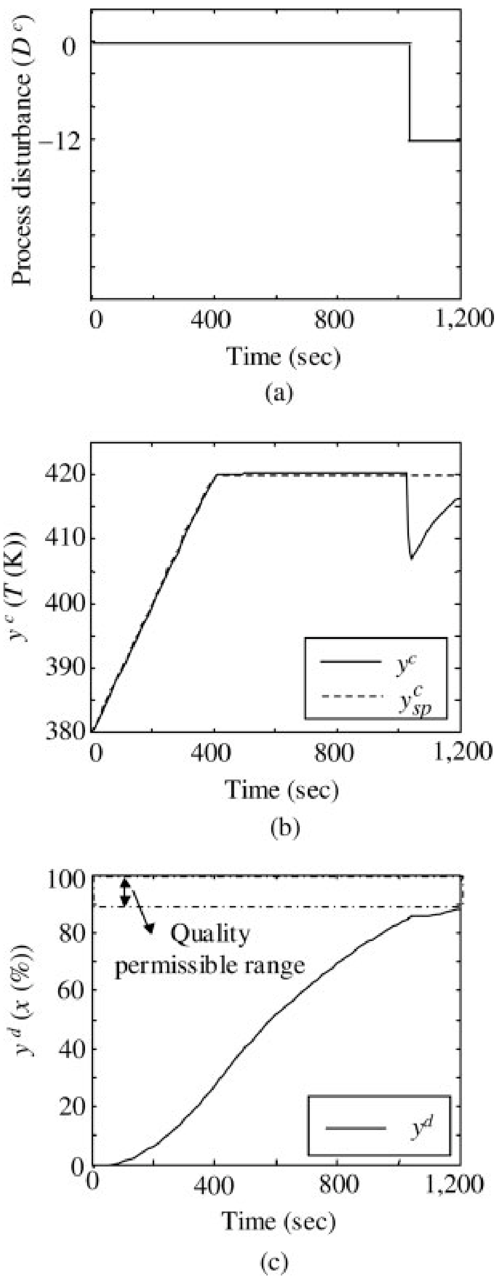


Figure 4. Process and product performance of the control system with only process controller under the process disturbance: (a) introduced process disturbance, (b) process controlled variable set-point and dynamics, and (c) product performance.

Process and Product Performance with IPP controller. The product quality problem identified earlier can be

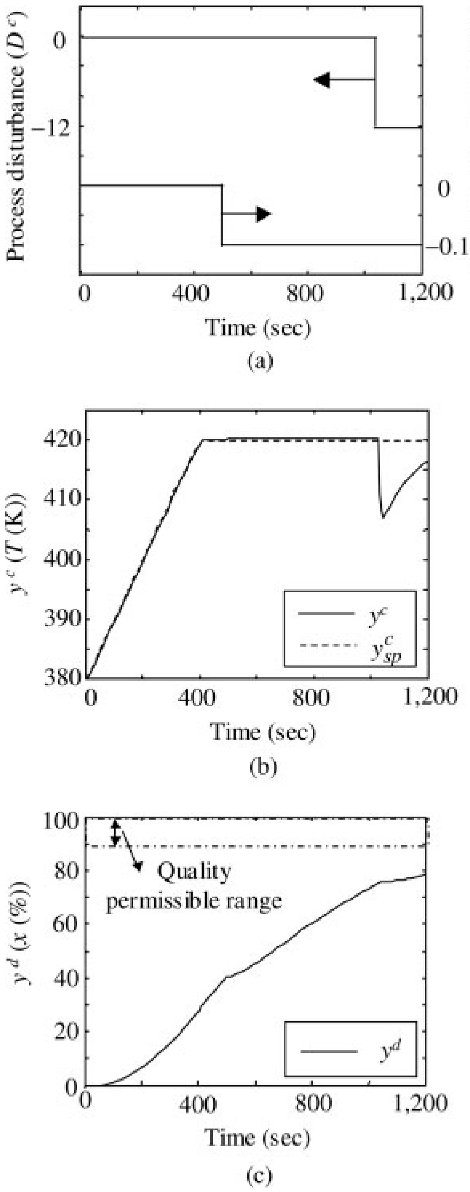


Figure 5. Process and product performance under both process and product disturbances (using only a process controller): (a) introduced process and product disturbances, (b) process controlled variable set-point and dynamics, and (c) product performance.

readily prevented by replacing the process controller by an IPP controller. In this case, the process controller is kept the same as the one earlier. The product controller can be derived through substituting Eq. 31 into Eq. 14. In this case, $\theta^{\rm d}$ equals to 10. This yields,

$$G_{\rm c}^{\rm d} = K_{\rm P}^{\rm d}\left(1 + \frac{1}{\tau_{\rm I}^{\rm d} s} + \tau_{\rm D}^{\rm d} s\right) \tag{37}$$

where the controller parameters are:

$$K_{\rm P}^{\rm d} = \frac{\tau_{\rm p}^{\rm d} + \tau^{\rm c,D}}{K_{\rm p}^{\rm d}\left(\tau^{\rm d,D} + \theta^{\rm c} + \theta^{\rm d}\right)} = 902.4 \tag{38}$$

$$\tau_{\rm I}^{\rm d} = \tau_{\rm p}^{\rm d} + \tau^{\rm c,D} = 705 \tag{39}$$

$$\tau_{\rm D}^{\rm d} = \frac{\tau^{\rm c,D}\tau_{\rm p}^{\rm d}}{\tau_{\rm p}^{\rm d} + \tau^{\rm c,D}} = 4.96 \tag{40}$$

System Under Process Disturbance. The process disturbance in this case (Figure 6a) is the same as that depicted in Figure 4a. Using the IPP controller, the process performance is acceptable, i.e., the process controlled variable, $y^{\rm c}$, moves

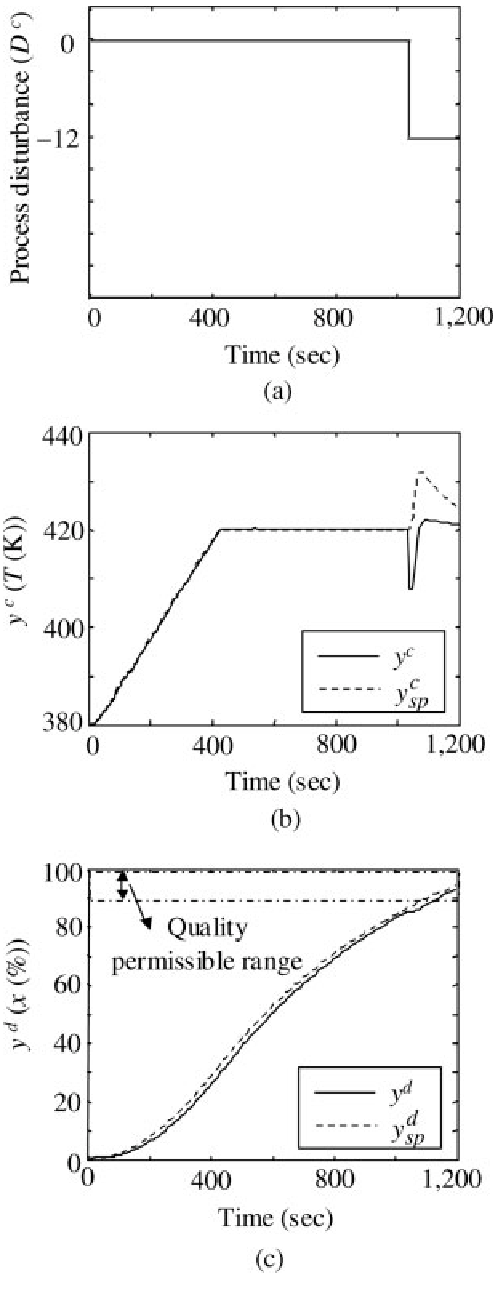
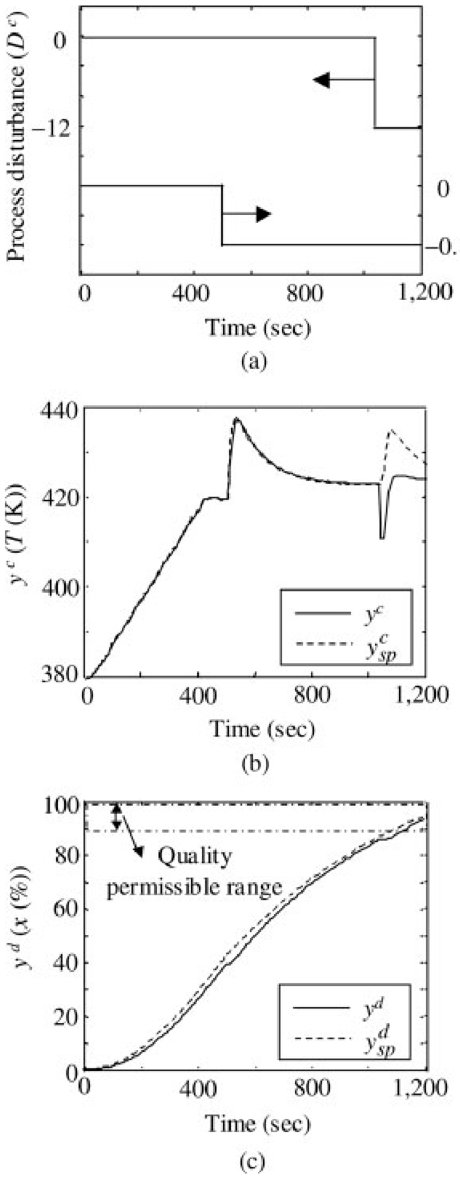


Figure 6. Process and product performance under the process disturbance (using an IPP controller): (a) introduced process disturbance, (b) process controlled variable set-point and dynamics, and (c) product controlled variable set-point and dynamics.



(a)

(b)

(c)

Figure 7. Process and product performance under both process and product disturbances (using the IPP controller): (a) introduced process and product disturbances, (b) process controlled variable set-point and dynamics, and (c) product controlled variable set-point and dynamics.

quickly back to the nominal condition after the disturbance enters (see, Figure 6b). This is different from Figure 4b where only a process controller is used. Note that with the IPP controller, the set-point of the process controller is changed, as a response to the appearance of the process disturbance. Figure 6c shows that the product quality is all-time ensured, regardless of the process disturbance. The quality problem shown in Figure 4c is prevented with this the IPP controller.

System Under Both Process and Product Disturbances. The adoption of the IPP controller can demonstrate further attractiveness in both process and product control. Figure 7a shows the occurrence of both the process disturbance and the product disturbance, which are the same as those shown in Figure 5a. Using the IPP controller, the process controller has a very different set-point profile (see, the comparison between Figures 7b and 5b). The product quality in this case is ensured, regardless of the appearance of both types of disturbances (see, Figure 7c). The serious product quality problem shown in Figure 5c is now completely eliminated.

Case II: Bidirectional Interactive Process and Product System

The process and product system with bidirectional interaction is shown in Figure 3, where, for simplicity, G_a^c, G_m^c, and G_m^d are all set to "1". Both the process and the product are modeled as first-order systems, i.e.,

$$G_p^c = \frac{K_p^c}{\tau_p^c s + 1} = \frac{0.5}{1.25s + 1} \tag{41}$$

$$G_p^d = \frac{K_p^d}{\tau_p^d s + 1} = \frac{0.4}{2s + 1} \tag{42}$$

The product has effect on the process through a first-order transfer function, i.e.,

$$G_d^{dc} = \frac{37.5}{2.5s + 1} \tag{43}$$

This system experiences both product disturbance and process disturbance. The transfer functions for these disturbances are respectively:

$$G_d^c = \frac{20}{6s + 1} \tag{44}$$

$$G_d^d = \frac{10}{5s + 1} \tag{45}$$

In this case, the desired closed-loop time constants for the process and the product, $\tau^{c,D}$ and $\tau^{d,D}$, are both set to 0.1.

Process and Product Performance with Only Process Controller. The system is firstly studied using only a process controller. The process controller for the system is a PI controller (Eq. 20) with the control parameter determination formulas in Eqs. 21, 22 (in this case, θ^c equals to 0); they are:

$$K_P^c = \frac{\tau_P^c}{K_p^c\left(\tau^{c,D} + \theta^c\right)} = 25 \tag{46}$$

$$\tau_I^c = \tau_P^c = 1.25 \tag{47}$$

System Performance Under no Process and Product Disturbances. Since this system experiences bidirectional interaction between the process and the product, it is understandable that even under no process and product disturbances, the designed process controller may have difficulty in achieving satisfactory process performance. If the interaction between the process and the product is very strong, then the product quality may have severe problems. As shown in Figure 8, both

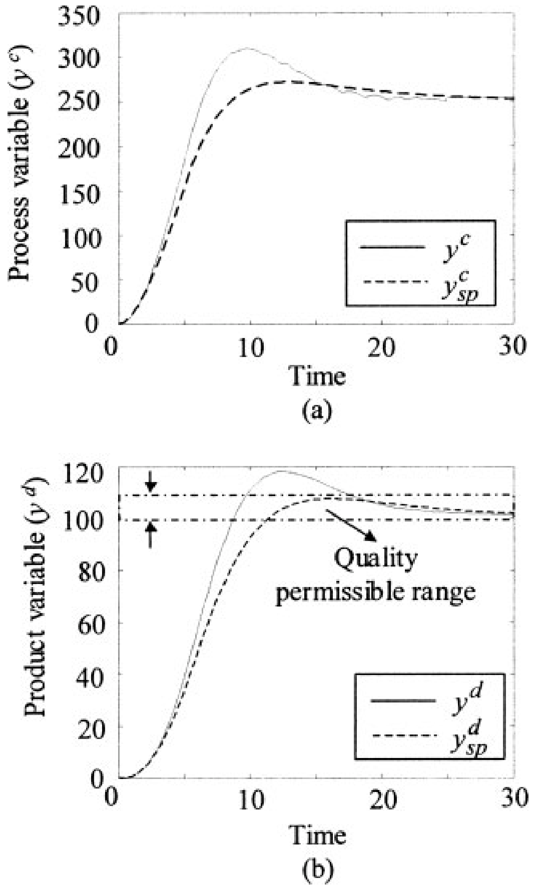


Figure 8. Process and product performance under no disturbance (using only a process controller): (a) process controlled variable set-point and dynamics, and (b) product controlled variable dynamics.

the process controlled variable and the product variable deviates from their set-points for at least one third of the total processing time. Although the final product quality is in the permissible range (see, Figure 8b), the dynamic product performance, which exhibits a large overshoot, is not preferable.

System Performance Under Both Process and Product Disturbances. When process and product disturbances are introduced into the system, the control performance becomes much worse. Figure 9a shows a product disturbance occurring at the 10th min, with a change from 0 to −5, and a process disturbance occurring at the 25th min, with a change from 0 to −20. The dynamics of the process controlled variable is similar to the dynamics in the case where no disturbance is introduced (see, comparison between Figure 9b and Figure 8a). However, the product quality is completely damaged starting from the 13th min in this case due to the introduction of disturbances (see, Figure 9c and comparison with Figure 8b).

Process and Product Performance with IPP controller. As discussed earlier, the process controller alone cannot ensure product quality even when the system does not experience any disturbances. An IPP controller can provide a very different result. In the IPP controller, the process controller is kept the same as the one earlier. The product controller can be derived through substituting Eq. 42 into Eq. 14. In this case, θ^c and θ^d are equal to 0. This yields,

$$G_c^d = K_P^d\left(1 + \frac{1}{\tau_I^d s} + \tau_D^d s\right) \tag{48}$$

where the controller parameters are:

$$K_P^d = \frac{\tau_p^d + \tau^{c,D}}{K_p^d\left(\tau^{d,D} + \theta^c + \theta^d\right)} = 52.5 \tag{49}$$

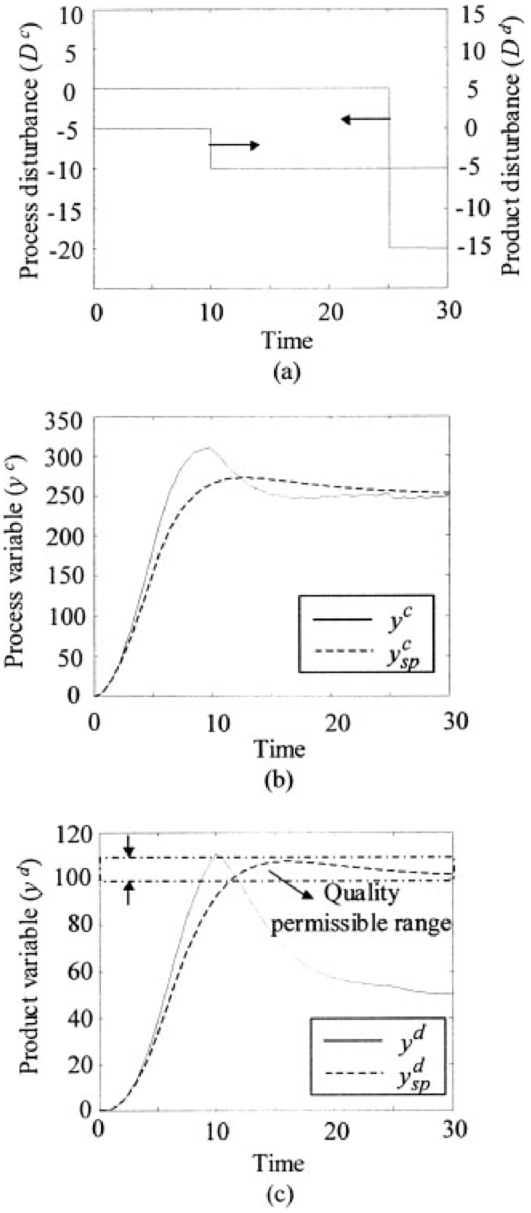
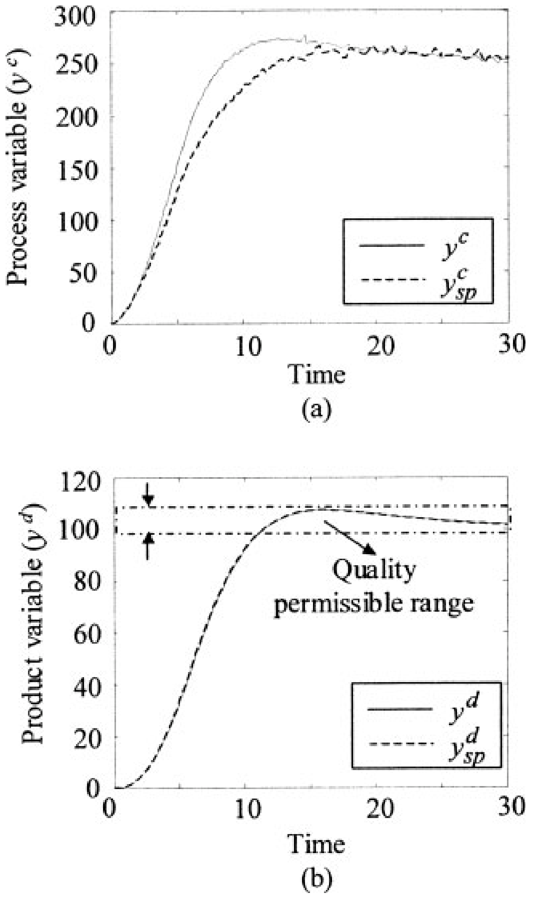


Figure 9. Process and product performance under both process and product disturbances (using only a process controller): (a) introduced process and product disturbances, (b) process controlled variable set-point and dynamics, and (c) product controlled variable dynamics.



(a)

(b)

Figure 10. Process and product performance under no disturbance (using IPP controller): (a) process controlled variable set-point and dynamics, and (b) product controlled variable set-point and dynamics.

$$\tau_I^d = \tau_p^d + \tau^{c,D} = 2.1 \tag{50}$$

$$\tau_D^d = \frac{\tau^{c,D}\tau_p^d}{\tau_p^d + \tau_{c,D}} = 0.095 \tag{51}$$

System Performance Under no Process and Product Disturbances. As shown in Figure 10, with the IPP controller, the product quality can be perfectly controlled regardless of the bidirectional interaction between process and product. Although the process controlled variable deviates from the set-point slightly, product performance improvement can be clearly demonstrated through comparison between Figures 10b and 8b.

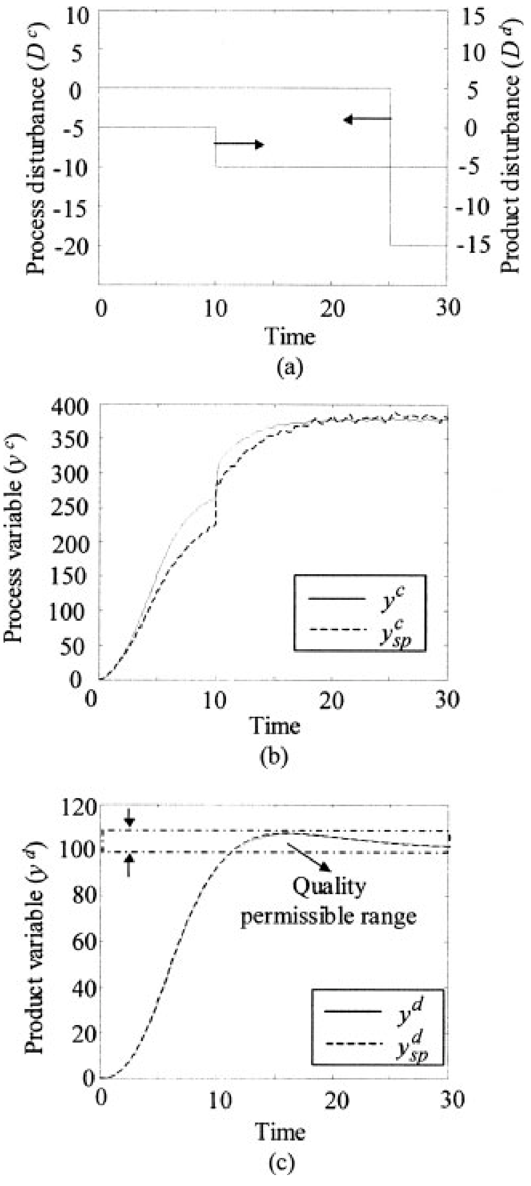
System Performance Under Both Process and Product Disturbances. The use of the IPP controller can demonstrate more attractive advantages in disturbance rejection for dynamic product QC. Figure 11a gives the process and product disturbance profile, which are the same as that in Figure 9a. Interestingly, the process set-point profile in Figure 11b is very different from that in Figure 9b. The perfect product performance under IPP control is shown in Figure 11c. The situation of damaged product quality shown in Figure 9c is now completely eliminated.

Remarks

The advantage of using IPP control over traditional process control has been further demonstrated in the two case studies.

(a). It is shown that the quality of the process dynamic alone may not be used to judge product quality at all, which has been shown in the two examples.

Example in Case I: Under the two types of disturbances defined in Figure 5a, the process dynamic performance is quite satisfactory as shown in Figure 5b. Nevertheless, the product quality is completely damaged after the first disturbance enters (see Figure 5c).



(a)

(b)

(c)

Figure 11. Process and product performance under both process and product disturbances (using IPP controller): (a) introduced process and product disturbances, (b) process controlled variable set-point and dynamics, and (c) product controlled variable set-point and dynamics.

Examples in Case II: Under two types of disturbances shown in Figure 9a, the process dynamic performance in Figure 9b looks quite acceptable in terms of set-point tracking. However, the product quality is entirely not acceptable as shown in Figure 9c. Figure 11 shows an example of using IPP control that provides opposite result even though the same disturbances are introduced (see Figure 11a). The process controlled variable has a relatively poor set-point tracking performance during the first half period of the operation (see Figure 11b). It seems reasonable to suspect that this might cause some product quality problem eventually. However, under the IPP control, the product quality was ensured within the permissible range (see Figure 11c).

(b). The case studies involve the first-order or first-order-plus-time-delay process and product systems. If a process or product model is of the second or high order, it can be reduced to a first-order-plus-time-delay model.[14] Then the introduced controller design methodology can be directly used. Nevertheless, model reduction is not mandatory for the design methodology. The only difference is that the resulting control laws of the IPP controller will not be in the standard PID form.

(c). For a nonlinear system, if it is suitable to be linearized around the normal operating point, a linear model is suggested to be used and thus the proposed IPP controller design methodology can be used (see Case I). If a single-point linearization is not sufficient, a piecewise linearization method is suggested for the nonlinear system. The proposed controller design methodology can still be used. In this case, there will be a set of controller parameters, each of which will be applicable to a specific linearization zone in the piecewise linearization process. On the other hand, if piecewise linearization of a highly nonlinear process and product model is not preferable for some reason, nonlinear MPC techniques could be appropriate for problem solving and the basic philosophy of IPPC is still valid, i.e., to design an inner loop for process control, and to generate an outer loop for product control.

(d). It is highly desirable to realize product model predictive control (MPC), as if product quality can be predicted in a large number of succeeding steps, then product dynamic control can be adjusted much earlier. It is well known that MPC has demonstrated great success in industrial process control.[13] The process MPC design methodology can be used to realize product MPC design as well.

Conclusions

Product QC has been mostly relied on postprocess inspection in many manufacturing systems. It has been shown that this type of reactive QC is frequently insufficient. Product quality problems should be prevented from the earliest stage of manufacturing steps where those quality deficiencies may start to shown. This suggests a realization of real-time closed-loop control. This study shows, however, that closed-loop process control alone is not sufficient at all for quality problem prevention. In fact, even if process dynamic performance is satisfactory, product quality may still have even a serious problem. A truly *proactive* product QC approach is to realize IPP control. The developed IPP controller design methodology is general and it is virtually applicable for any types of linear SISO process and product systems. The case studies have evidently demonstrated the efficacy and attractiveness of the IPP controller design methodology.

IPP control is an in-process, “all-time”, “on-aim” proactive QC approach. It must be pointed out that the use of IPP control is by no means to replace postprocess inspection-based QC. Note that under IPP control, a large number of quality problems can be prevented during manufacturing process. Nevertheless, there could be other quality problems that were not modeled, predicted, and thus prevented in manufacturing. Inspection-based QC will play a key role in identifying them in the final products.

Acknowledgments

This work is in part supported by U.S. NSF (CTS 0091398) and the Institute of Manufacturing Research of Wayne State University to the Y. H., by China NSF to the Y. Q., and by US NSF (CTS 0407494) to the H. H. L.

Literature Cited

1. Kane VE. *Defect Prevention: Use of Simple Statistical Tools*. New York: Mercel Dekker, 1989.
2. Luyben WL, Luyben ML. *Essentials of Process Control*. New York: McGraw-Hill Companies, 1997.
3. Wu SM, Ni J, Hu S. Next generation quality control in manufacturing-real time defect prevention. *In Proceeding of the ASME Winter Annual Meeting*. San Francisco, CA, 1989.
4. Yabuki Y, MacGregor JF. Product quality control in semibatch reactors using midcourse correction policies. *Ind Eng Chem Res*. 1997; 36:1268–1275.
5. Wang Y, Doyle FJ. Reachability of particle size distribution in semibatch emulsion polymerization. *AIChE J*. 2004;50:3049–3059.
6. Lou HH, Huang YL. Integrated modeling and simulation for improved reactive drying of clearcoat. *Ind Eng Chem Res*. 2000;38: 500–507.
7. Lou HH, Huang YL. Hierarchical decision making for proactive quality control: system development for defect reduction in automotive coating operations. *Eng Appl Artif Intell*. 2003;16:237–250.
8. Xiao J, Li J, Lou HH, Huang YL. Cure-window-based proactive quality control in topcoat curing. *Ind Eng Chem Res*. 2006;45:2331–2340.
9. Xiao J, Li J, Lou HH, Xu Q, Huang YL. ACS-based dynamic optimization for curing of polymeric coating. *AIChE J*. 2006;52:1410–1422.
10. Bequette BW. *Process Dynamics: Modeling, Analysis, and Simulation*. New Jersey:Prentice Hall PTR, 1998.
11. Ogunnaike BA, Ray WH. *Process Dynamics, Modeling, and Control*. New York:Oxford University Press, 1994.
12. Chen D, Seborg DE. PI/PID controller design based on direct synthesis and disturbance rejection. *Ind Eng Chem Res*. 2002;41:4807–4822.
13. Seborg DE, Edgar TF, Mellichamp DA. *Process Dynamics and Control*, 2nd ed. New York:Wiley, 2004.
14. Skogestad S. Simple analytic rules for model reduction and PID controller tuning. *J Process Control*. 2003;13:291–309.
15. Dickie RA, Bauer DR, Ward SM, Wagner DA. Modeling paint and adhesive cure in automotive applications. *Prog Org Coat*. 1997;31: 209–216.

Manuscript received July 3, 2006, and revision received Dec. 1, 2006.