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ScienceDirect
Automatica 43 (2007) 191–211
automatica
www.elsevier.com/locate/automatica

Cross-directional control of sheet and film processes☆

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Received 28 May 2000; received in revised form 16 February 2006; accepted 19 July 2006

Abstract

Sheet and film processes include polymer film extrusion, coating processes of many types, paper manufacturing, sheet metal rolling, and plate glass manufacture. Identification, estimation, monitoring, and control of sheet and film processes are of substantial industrial interest since effective control means reduced usage of raw materials, increased production rates, improved product quality, elimination of product rejects, and reduced energy consumption. This paper reviews recent developments in sheet and film process control with particular attention to the effectiveness of existing techniques at addressing the critical aspects of sheet and film processes.

Keywords: Large-scale systems; Robust control; Singular value analysis

1. Introduction

The identification, estimation, monitoring, and control of sheet and film processes (Featherstone, VanAntwerp, & Braatz, 2000), which include coating (Ismail, Dumont, & Backstrom, 2003), paper manufacturing, metal rolling (Bulut, Katebi, & Grimble, 2002; Duncan, Allwood, & Garimella, 1998; McDonald, Spooner, Cockerell, Edwards, & Thomas, 1993), and polymer film extrusion processes, are of substantial industrial interest. Coating processes are of great importance to manufacturing—especially in the photographic, magnetic and optical memory, electronic, and adhesive industries. The total capitalization of industries which rely on coating technology has been estimated to be over a trillion US dollars worldwide (Cohen, 1990). Paper manufacturing is the mainstay of the pulp and paper industries; and polymer film extrusion is used to make a wide variety of products, from plastic films for windshield safety glass to large plastic bags (Callari, 1990; Martino, 1991). Approximately, 90% of the steel, aluminum, and copper produced worldwide is rolled (Garimella & Srinivasan, 1998). Improved control of sheet and film properties can mean significant reductions in material consumption, greater production rates for existing equipment, improved product quality despite inexperienced operators resulting from a high turnover rate in the work force, elimination of product rejects, and reduced energy consumption (Åström, 1970; Atkins, Rodencal, & Vickery, 1982; Boyle, 1978; Callari, 1990; Carey, Bietry, & Stoll, 1975; Haverinen, 1983; Karlsson & Haglund, 1983; King, 1976; Nuyan, 1986; Schroeder, 1992; Wallace, 1981, 1986).

The process control problem for sheet and film processes is typically separated into two main control objectives. One is the maintenance of uniform thickness along the length of the sheet or film (see Fig. 1), which is referred to as the *machine-direction* (MD) control problem (Smook, 1992), since the sheet or film travels through the machine in this direction. Figs. 2 and 3 show the large-scale nature of these machines. The MD problem (Åström, Borisson, Ljung, & Wittenmark, 1977; Åström & Wittenmark, 1973; Bialkowski, 1978, 1983; Cegrell & Hedqvist, 1975; Fjeld & Wilhelm, 1981; Ma & Williams, 1988; Rantala & Kokkonen, 1986; Sikora, Bialkowski, MacGregor, & Tayler, 1984) and many related single loop problems (Borison, 1979; D' Hulster, de Keyser, & van Cauwenberghe, 1983; Fjeld, 1978; Ng, Arden, & French, 1991; Saif, 1993)

☆ This paper was not presented at any IFAC meeting. This paper was recommended for publication in revised form by Editor M. Morari.

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0005-1098/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.automatica.2006.07.025

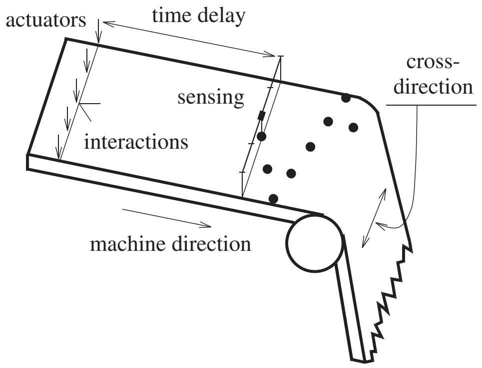

Fig. 1. Generic sheet or film process with scanning gauge (not drawn to scale).

has been studied extensively since the application of stochastic control to the problem by Åström in the late 1960s (Åström, 1967). A survey of the early work on MD control is provided by Brewster and Bjerring (1970), and of later work by Dumont (1986). The MD problem is generally dominated by the time delay of the process and this may have the effect of limiting the achievable closed-loop performance (Brinsmead & Goodwin, 2001). The second main control objective is the maintenance of uniform properties across the width of the machine (see Fig. 1)—this is referred to as the *cross-directional* (CD) control problem. This survey is primarily focused on the CD problem because this is generally considered to be much more difficult than the MD problem (Brewster, 1989).

This article reviews recent developments in sheet and film CD control, with particular attention to the effectiveness of existing techniques at addressing the critical aspects of sheet and film processes: the types of sensors, the large number of inputs and outputs, mismatch between the model and the true process, failing or faulty equipment, and constraints on actuator movements.

First we describe the characteristics of sheet and film processes, and models for these processes. Secondly, we assess the effectiveness of various approaches to controlling sheet and film process control, including model inverse-based control, linear quadratic control, antiwindup compensation, model predictive control (MPC), and robust control. This is followed by a review of techniques for profile estimation, model identification, and process monitoring.

2. Characteristics of sheet and film processes

Characteristics that make the effective control of sheet and film processes especially challenging (and interesting) are described here.

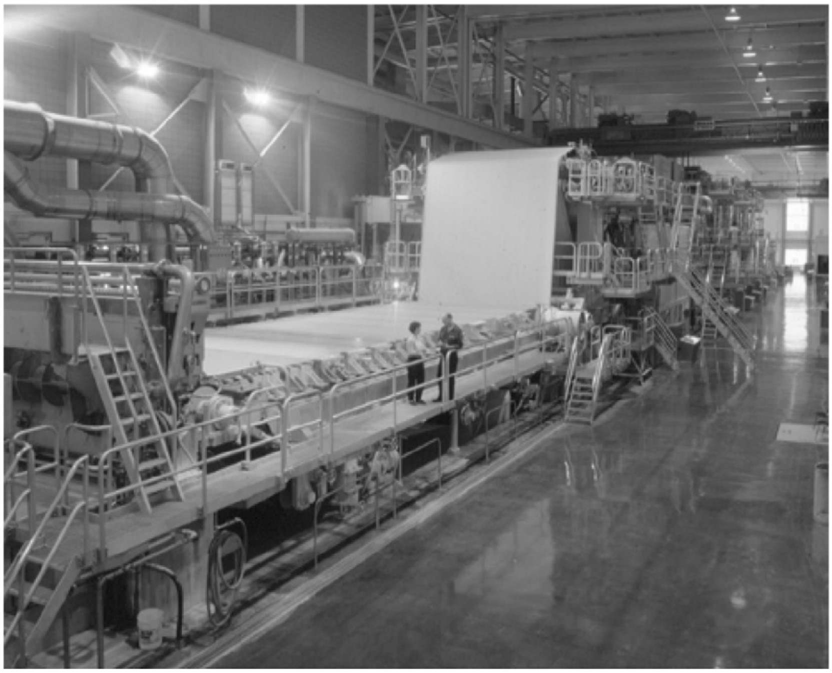

Fig. 2. An industrial paper machine (courtesy Consolidated Papers, Inc.).

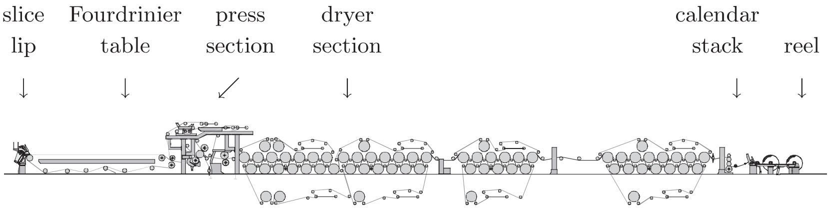

Fig. 3. Schematic diagram for a Fourdrinier-type paper machine (courtesy Metso Paper).

2.1. General features of sheet and film processes

This section briefly describes the commonalities and differences among various sheet and film processes. A more detailed description is provided elsewhere (Featherstone et al., 2000).

High-quality sheet and film products have uniform properties both across the sheet, called the CD, and along the length of the sheet, called the MD, as shown in Fig. 1. Control actions are effected at a distribution device, known as the *headbox* in papermaking, the *workroll* in metal rolling, and the *die* in coating and polymer extrusion processes. Actuators are almost always located at evenly spaced points along the CD.

In coating applications the fluid flows through a slot, and the actuators vary the amount of fluid flow at a location by changing the width of this slot, often by thermal-expansion bolts or motor- or hydraulic-driven screws (Braatz, Tyler, Morari, Pranckh, & Sartor, 1992a; Duncan, Allwood, Heath, & Corscadden, 2000; Kjaer, Heath, & Wellstead, 1994; Rastogi, 1978; Wallace, 1981). This is similar to metal rolling where metal feedstock is repeatedly pressed between rollers to flatten and stretch it into a thinner product. The force applied to the rollers is varied across the machine in order to control at various points the thickness of the metal sheet (Garimella & Srinivasan, 1994, 1998; Goodwin, Lee, Carlton, & Wallace, 1994; Hearns & Grimble, 2000; Ringwood, 1995; Ringwood, Owens, & Grimble, 1994). In polymer film extrusion, the actuators can be of several types. Choke bars (restricter bars) and flexible lips are used to adjust the widths of the die gap. These devices have a large number of screws or bolts across their widths that permit local adjustments (Charrier, 1991; Duncan et al., 2000; Wigotsky, 1996). Thickness variations can be controlled by adjusting the temperature of the polymer melt at the die surface (Callari, 1990; Hensen, 1988; Wigotsky, 1996). For example, valves that manipulate the air flow rate around a blown film die determine the local cooling of the polymer melt and hence thickness. A larger variety of actuators is found in paper machines, where actuation can be through slice lip variation, heat lamps, water jets, air jets, steam sprays, and/or magnetic induction heaters (Heaven, Vyse, Steele, & Hagart-Alexander, 1998; Henry, 1984; Lawrence, 1986; Nyberg & Malashenko, 1997, 1998; Shands, Sanford, & Rogers, 1995; Smook, 1992; Stewart, Gorinevsky, & Dumont, 2003a; Vyse, King, Heaven, & Pantaleo, 1996; Wang, Dumont, & Davies, 1993a,b). In many cases, multiple banks of actuators are used, with a substantial amount of space between actuator banks (King, 1976). No matter what mechanism is used for the manipulation of sheet or film properties, the actuator dynamics are usually assumed, at least nominally, to be identical within an actuator bank (Duncan et al., 2000; Laughlin, Morari, & Braatz, 1993; Pranckh, 1991; Wilhelm & Fjeld, 1983).

Processing usually occurs between actuator banks and sensing banks, with typical processing including draining, drying, pressing, steaming, heating, and stretching. During normal operation the processing is stable, and can usually be assumed to be linear (Boyle, 1978; Braatz et al., 1992a; Domanti, McElwain, Middleton, & Edwards, 1993) (an exception is in moisture control on a paper machine, Lindeborg, 1986a).

Sensing methods include beta-ray absorption, gamma-ray, X-ray absorption, X-ray fluorescence, infrared, microwave, visible light, magnetic, electric capacitance, force distribution, and ultrasonics (Cho, Pfeifer, & Utt, 1973; Cho, Utt, & Pfeifer, 1971; Cielo, Cole, & Favis, 1986; Domanti et al., 1993; Grimble, 1995a,b; Grimble & Fotakis, 1982; Kjaer, Wellstead, & Heath, 1996; Lenk, 1980; Pearson, 1976; Rutledge, 1986; Shelley, Booksh, Burgess, & Kowalski, 1996; Sivilotte, Davies, Henze, & Dahle, 1973; Smook, 1992) and typical sensor measurements include wet basis-weight, dry basis-weight, opacity, moisture, caliper, organic content, stress, shape, color, and paper formation (Åström, 1970; Beecher & Bareiss, 1970; Braatz et al., 1992a; Brewster & Bjerring, 1970; Bulut et al., 2002; Carney, Goodwin, Edwards, & Steigler, 1990; Chen, Murphy, & Subbarayan, 1996; Choi, Johnson, & Grimble, 1994; Ismail et al., 2003; Kan, 1987; Karlsson & Haglund, 1983; Nakayama, 1992; Pearson, 1976; Roth, 1986; Sivilotte et al., 1973; Smook, 1992). Since these sensor measurements are usually taken after some form of processing, they are typically located some distance down the MD from the actuation. This often results in a significant time delay between actuator manipulations and sensing of the result of these manipulations. The delay is time varying as the machine speed varies. Additional delay is often caused by sensor delay, for example, due to integrating-type sensors (Braatz et al., 1992a).

Among the many defects which can occur are variations in the film thickness, surface defects, low tensile strength, low impact strength, hazy film, blocking, and wrinkling. A major source of defects is tear or breakage of the web or sheet, and subsequently, the ability to produce product that meets quality specifications following a web break.

2.2. Traversing and full-scan sensors

Due to their high cost, usually only a few sensors are used to measure the uniformity of the sheet or film (e.g., a single sensor with the auxilary equipment necessary to operate the sensor can cost as much as $300,000 (Grimble & Fotakis, 1982; Toensmeier, 1991)). To provide measurements along the entire CD, these sensors are placed on tracks so as to continuously travel back and forth transverse to the movement of the sheet or film. Since the sheet or film moves in the MD, each sensor measures only a zigzag portion of the sheet or film, as illustrated in Fig. 1. It is from this limited number of noisy measurements that the entire sheet or film profile (that is, at all sensing locations) is estimated at each sampling time for use by the control algorithm (Duncan & Wellstead, 2004). These estimates can be obtained using a time-varying Kalman filter, as has been described by various authors (Bergh & MacGregor, 1987b; Halouskova, Karny, & Nagy, 1993; Tyler & Morari, 1995). The conventional procedure for separating the MD and CD variations, known as *exponential multiple-scan trending* (Smook, 1992; Taylor, 1991), weighs the current measurement at each CD position to its long-term historical value.

In the last several years sensors have become available which measure the profile of the entire sheet or film simultaneously (Chen & Subbarayan, 1999; Chen, Subbarayan, Kristinsson, & Snyder, 1998; Francis, Stenbak, & Kleinsmith, 1989; Kjaer, Wellstead, & Heath, 1997; Norbury, 1996; Poirier, Vyse, Hagart-Alexander, Heaven, & Ghofraniha, 1999; Vyse et al., 1998a,b). The CD profile can be measured as finely as every millimeter at rates of up to 120,000 times per minute (Anonymous, 1998). This could result in as many as 10,000 sensor measurements across the machine. In contrast to scanning sensors which provide limited data, such full scans provide so much data that algorithms need to be carefully designed to extract the maximum information from the data while being computationally efficient enough to complete all calculations on the controls computer during each sampling instance.

2.3. *Large numbers of variables*

Sheet and film processes can have hundreds of actuators (Callari, 1990; Fan & Dumont, 2001; Wilhelm & Fjeld, 1983) and up to 10,000 sensing locations (Anonymous, 1998; Kjaer et al., 1994). Moreover, an established trend is for new machines to have smaller spacing between neighboring actuators and neighboring sensing locations, which increases the dimension of the system (Wallace, 1981). This makes control more challenging because: (i) most off-the-shelf controller synthesis programs have numerical inaccuracies for processes with a large number of inputs and outputs (Hovd, Braatz, & Skogestad, 1993) (this is not to say that the algorithms are inherently nonrobust; only that the implementations can be nonrobust); (ii) even with the processing speeds achievable by modern control hardware, the high-speed nature of these machines place constraints on the amount of on-line computation available for the control algorithm (Bialkowski, 1988; Braatz et al., 1992a; Dumont, 1990; Heaven, Jonsson, Kean, Manness, & Vyse, 1994; Kan, 1987; Young, Lowery, & Plummer, 1986); and (iii) processes of large dimension tend to have plant matrices which are poorly conditioned (Russell & Braatz, 2002), and such processes are well known to be difficult to identify (Andersen & Kummel, 1992a,b; Featherstone & Braatz, 1998b; Jacobsen, 1994; Koung & MacGregor, 1994; Lee, Cho, & Edgar, 1998; Li & Lee, 1996) and control (Braatz, Lee, & Morari, 1996; Braatz & Morari, 1994; Grosdidier, Morari, & Holt, 1985; Lee, Braatz, Morari, & Packard, 1995; Russell & Braatz, 2002; Skogestad, Morari, & Doyle, 1988).

2.4. *Plant/model mismatch*

In practice it is impossible to generate a highly accurate sheet and film process model, either phenomenologically or via input–output identification, because of inaccurate values for the physical parameters of the sheet and film process, CD movement of the entire sheet or film web including shrinkage or stretching (Fu & Nuyan, 1999; Gallay, 1973; Lindeborg, 1986b; Matsuda, 1990; McFarlin, 1983; Wadhams, I'Anson, James, & Kropholler, 1991), lack of complete understanding of the underlying physical phenomena (for example, during drying) (Braatz, 1994), unknown disturbances (Grimble & Fotakis, 1982; Peterson, 1992; Schweiger & Rudd, 1996), equipment aging (Duncan, 1994a), wear changing the dynamics of the process (Ismail et al., 2003), and static friction, metal fatigue, and metal relaxation associated with actuation (Åström, 1970; Beecher & Bareiss, 1970; Braatz et al., 1992a; McFarlin, 1983; Pranckh, 1991).

2.5. *Faults and failures*

Equipment faults and failures are common during normal sheet and film process operations. Common problems include poor or broken electrical connections, mechanical breakages in strain gauges used to keep track of actuator movements, and frozen bolts or stripped screws used to implement actuator movements (Pranckh, 1991).

2.6. *Constraints*

Actuator positions for sheet and film processes are usually constrained. In cases where the actuators are steam sprays or heaters, excessive actuator movements may weaken or tear the sheet or film. In cases where the actuators are physically connected, these constraints prevent excessive mechanical stresses (Braatz et al., 1992a; Carey et al., 1975; McFarlin, 1983; Nuyan, 1986; Richards, 1982; Ringwood & Grimble, 1990; Wilkinson & Hering, 1983).

There are four types of constraints on the actuator positions:

1. Each actuator position u_i may be constrained from being too large or too small, that is, $u_{\min} \leqslant u_i \leqslant u_{\max}$, for $i = 1, \ldots, n$. These are known as min–max constraints.
2. The differences between adjacent actuator positions u_i may be limited, that is, $|\delta u_i| = |u_{i+1} - u_i| \leqslant |\delta u|_{\max}$, for $i = 1, \ldots, n-1$. These constraints are often called first-order bending moment constraints.
3. The amount of "zigzag" that can be introduced among neighboring actuators is limited by a second-order bending constraint. These take the form $|\delta^2 u_i| = |u_{i+2} - 2u_{i+1} + u_i| \leqslant |\delta^2 u|_{\max}$, for $i = 1, \ldots, n-2$.
4. The rate at which actuator settings can be changed may be limited. These rate constraints take the form $|u_i(k+1) - u_i(k)| \leqslant |\delta u_t|_{\max}$, for $i = 1, \ldots, n$, where k is a sampling instance (the time index).

Any subset of these constraints can be important for a particular sheet and film process.

The practice of "clipping" the control actions so that the constraints are satisfied (as illustrated in Fig. 4) will decrease the controller gain and change the direction of the control actions. This change of control direction can seriously degrade the closed-loop performance (Campo, 1990; Segall, MacGregor, & Wright, 1991). On the other hand, scaling control actions as shown in Fig. 4 decreases the controller gain without changing the input direction. This can cause some loss in closed-loop performance for some processes, but it gives better performance than clipping (Campo & Morari, 1990). Scaling performed well for an industrial adhesive coater as reported in Braatz, Tyler, and Morari (1992) and Braatz et al. (1992a). Depending on the

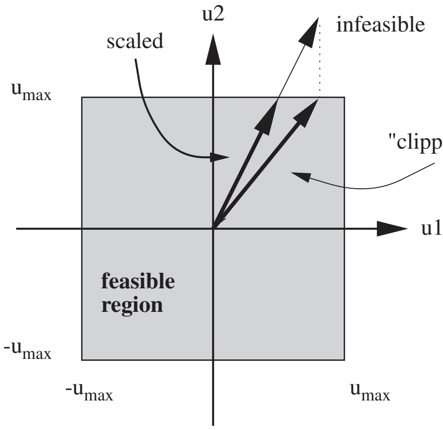

Fig. 4. Uncompensated actuator constraints may change the direction of the input whereas directionality compensation does not.

process, constraint handling may be needed when the disturbances are sufficiently large and have sharp spatial variations across the sheet or film, or when actuator interactions are non-negligible (Braatz et al., 1992a).

2.7. Models for sheet and film processes

This section briefly describes model structures which are appropriate for sheet and film processes. When an actuator is manipulated, sheet or film properties usually change for some distance on either side of the position directly downstream from the actuator. These interactions are caused by fluid flow within the sheet or film, processing between actuator and sensor banks, and/or physical connections between actuators within an actuator bank. To simplify presentation only, discussions will be primarily in terms of one actuator bank and one sensor bank.

The observed interactions are typically incorporated into the profile response model with n actuators and h interaction parameters through a *constant* matrix $P_{\mathrm{CD}}^{n,h}$. Then the overall dynamic model $P_{\mathrm{CD}}^{n,h}(s)$ is given by the product of scalar dynamics (associated with the actuation, processing, and sensing) and the interaction matrix $P_{\mathrm{CD}}^{n,h}$. Early work on CD control assumed that the interactions took one of the following three forms shown in Table 1: centrosymmetric, Toeplitz symmetric, and circulant symmetric. The assumptions regarding the nature of the interactions determine the appropriate model structure. Assumptions that accompany each model structure have been detailed by Laughlin et al. (1993) and are summarized below. Whether or not the assumptions are accurate can mean success or failure of the control system design based on one of these models (Featherstone & Braatz, 1997).

Table 1
Three model structures relevant to sheet and film processes: (a) centrosymmetric, (b) Toeplitz symmetric, and (c) circulant symmetric

(a)

$$P_{\mathrm{CD}}^{n,h}=P_{\mathrm{C}}^{n,h}=\underbrace{\begin{pmatrix}
p_{11} & p_{12} & \cdots & p_{1h} & 0 & \cdots & \cdots & \cdots & \cdots & 0\\
p_{21} & p_{22} & p_{23} & \cdots & p_{2h} & 0 & \ddots & \ddots & \ddots & \vdots\\
\vdots & p_{32} & \ddots & \ddots & \cdots & \ddots & \ddots & \ddots & \ddots & \vdots\\
p_{h1} & \vdots & \ddots & p_{hh} & \ddots & \cdots & \ddots & \ddots & \ddots & \vdots\\
0 & p_{h2} & \vdots & \ddots & \ddots & \ddots & \vdots & \ddots & 0 & \vdots\\
\vdots & 0 & \ddots & \vdots & \ddots & \ddots & \ddots & \vdots & p_{h2} & 0\\
\vdots & \ddots & \ddots & \ddots & \cdots & \ddots & p_{hh} & \ddots & \vdots & p_{h1}\\
\vdots & \ddots & \ddots & \ddots & \ddots & \cdots & \ddots & \ddots & p_{32} & \vdots\\
\vdots & \ddots & \ddots & \ddots & 0 & p_{2h} & \cdots & p_{23} & p_{22} & p_{21}\\
0 & \cdots & \cdots & \cdots & \cdots & 0 & p_{1h} & \cdots & p_{12} & p_{11}
\end{pmatrix}}_{n\times n}$$

(b)

$$P_{\mathrm{CD}}^{n,h}=P_{\mathrm{T}}^{n,h}=\underbrace{\begin{pmatrix}
p_1 & p_2 & \cdots & p_h & 0 & \cdots & \cdots & 0\\
p_2 & p_1 & p_2 & \cdots & p_h & \ddots & \ddots & \vdots\\
\vdots & p_2 & p_1 & p_2 & \cdots & \ddots & \ddots & \vdots\\
p_h & \vdots & p_2 & \ddots & \ddots & \vdots & p_h & 0\\
0 & p_h & \vdots & \ddots & \ddots & p_2 & \vdots & p_h\\
\vdots & \ddots & \ddots & \cdots & p_2 & p_1 & p_2 & \vdots\\
\vdots & \ddots & \ddots & p_h & \cdots & p_2 & p_1 & p_2\\
0 & \cdots & \cdots & 0 & p_h & \cdots & p_2 & p_1
\end{pmatrix}}_{n\times n}$$

(c)

$$P_{\mathrm{CD}}^{n,h}=P_{\mathrm{CS}}^{n,h}=\underbrace{\begin{pmatrix}
p_1 & p_2 & \cdots & p_h & 0 & \cdots & 0 & p_h & \cdots & p_2\\
p_2 & p_1 & p_2 & \cdots & p_h & 0 & \cdots & \ddots & \ddots & \vdots\\
\vdots & p_2 & p_1 & p_2 & \cdots & p_h & \ddots & \ddots & \ddots & p_h\\
p_h & \vdots & p_2 & p_1 & p_2 & \cdots & \ddots & \ddots & \vdots & 0\\
0 & p_h & \vdots & p_2 & \ddots & \ddots & \vdots & p_h & 0 & \vdots\\
\vdots & 0 & p_h & \vdots & \ddots & \ddots & p_2 & \vdots & p_h & 0\\
0 & \vdots & \ddots & \ddots & \cdots & p_2 & p_1 & p_2 & \vdots & p_h\\
p_h & \ddots & \ddots & \ddots & p_h & \cdots & p_2 & p_1 & p_2 & \vdots\\
\vdots & \ddots & \ddots & \cdots & 0 & p_h & \cdots & p_2 & p_1 & p_2\\
p_2 & \cdots & p_h & 0 & \cdots & 0 & p_h & \cdots & p_2 & p_1
\end{pmatrix}}_{n\times n}$$

Though the definitions of these matrices is standard in the mathematical literature (Bellman, 1960; Davis, 1979), the first to use these terms to refer to the model structures seems to be Laughlin et al. (1993)

Centrosymmetric: Centrosymmetric models have elements that are symmetric about the center of the matrix. If a machine were constructed such that the profile response (that is, the measured effect on the profile from stepping the actuators) was symmetric with respect to a vertical plane through the center of the sheet or film, then it would be *exactly* centrosymmetric. Centrosymmetric models can represent edge effects, that is, slight differences in response observed at different distances from the center of the sheet. An example of a centrosymmetric model structure is given in Table 1. If it is further assumed that the effect of actuator adjustment at position i on response at position j is the same as that at position j on response at position i, then the model structure is centrosymmetric *symmetric*.

Toeplitz symmetric: In Toeplitz symmetric models the same element is repeated along each diagonal of the matrix (see Table 1). This model follows from the assumption that changes observed downstream from one actuator caused by adjustments at the nearest neighboring actuators are independent of position across the machine. This is the model structure most often found in the literature (Dumont, 1990; Laughlin et al., 1993).

Circulant symmetric: Circulant symmetric matrices are both Toeplitz symmetric and centrosymmetric (see Table 1). As such, this model structure represents interactions for *circular* sheet or film processes, such as blown film extruders (Callari, 1990; Martino, 1991).

The above structures assume that the number of actuators is equal to the number of sensing locations. While this was true for early implementations of CD control to sheet and film processes, modern processes usually have the number of sensing locations much larger than the number of actuators. Most industrial control algorithms use a nonsquare matrix to transform the vector of sensor readings so that it has the same dimension as the vector of actuator signals, and then it is assumed that the interaction matrix between the actuator vector and transformed sensor vector has one of the structures in Table 1 (Gorinevsky, Heaven, & Vyse, 1996; Stewart, Gorinevsky, & Dumont, 1999; Stewart et al., 2003a). For many processes, the spatial response to a single actuator move changes from actuator to actuator (Heaven, Manness, Vu, & Vyse, 1996; Siler, 1984), which causes this latter assumption to be violated. For this reason, recent studies have considered processes with arbitrary nonsquare interaction matrices (Featherstone & Braatz, 1998c; VanAntwerp & Braatz, 2000a).

There have also been extensive developments in modeling sheet and film processes using two-dimensional state space or transfer function representations (Russell, Power, & Braatz, 1997; Wellstead, Zarrop, & Duncan, 2000; Wellstead, Zarrop, Heath, Kjaer, & Troyas, 1996), where one dimension is in the CD, and the other is in the MD. An advantage of such models is the ability to clearly represent the coupling of the MD and CD directions. However, the analytical and computational complexity of dealing with such models has limited their use mostly to academic studies (Wellstead et al., 1996).

3. Review

The plastic film industry began implementing CD control in the early 1970s (although not much of this work seems to have been published (Wallace, 1986)). CD control was first implemented to metal rolling machines in the mid-1970s (Bravington, Barry, & McClure, 1976; Spooner & Bryant, 1976; Van Haperen & Kilmister, 1976). The first implementation of CD control on paper machines occurred in 1977 (Smook, 1992); however, widespread use of such systems did not occur until the 1980s (Henry, 1984; Smith, 1985; Wilhelm & Fjeld, 1983). The control of CD variations in blade coaters became widespread in the early 1990s (Braatz et al., 1992a; Braatz, Tyler, Morari, Pranckh, & Sartor, 1992b; Vyse, King, Heaven, & Mononen, 1996). The large-dimension, uncertain, fault-prevalent, and constrained nature of sheet and film processes makes their control especially interesting and challenging. Here, we review the literature on sheet and film process control, and discuss how this research has addressed the characteristics of sheet and film processes.

3.1. Linear control

The two main CD control schemes reported in the literature before 1988 were linear quadratic optimal (Bergh & MacGregor, 1987a; Boyle, 1978; Richards, 1982; Tong, 1976; Wilhelm & Fjeld, 1983) and model inverse-based control (Beecher & Bareiss, 1970; Wilkinson & Hering, 1983). These CD control algorithms continue to be implemented on some machines (Dumont, 1990; Goodwin, Carney, & Edwards, 1990; Heaven et al., 1994; Heaven et al., 1996). Mostly steady-state models were used, with new control actions often taken only after steady state was reached. This is equivalent to treating the process dynamics as being entirely due to a time delay, which is a good assumption for many sheet and film processes. Linear quadratic optimal control was applied to dynamic models in later studies (Corscadden & Duncan, 2000; Duncan & Bryant, 1994; Tyler & Morari, 1995). The linear quadratic optimal controller for two-dimensional models of sheet and film processes was also derived (Heath & Wellstead, 1995a,b).

Analysis and linear controller design for circulant symmetric processes (described in Section 2.7) has been studied by many researchers, although not usually within the context of sheet and film process control (Fagnani & Willems, 1993, 1994; Hazewinkel & Martin, 1983a,b; Hazewinkel & Martin, 1984; Lunze, 1986, 1989; Martin, 1982; Wall, Willsky, & Sandell, 1979). The model structure can be exploited to simplify the design of decentralized (Abraham & Lunze, 1991; Sundareshan & Elbanna, 1991; Wall et al., 1979), linear quadratic (Brockett & Willems, 1974), and H_∞ optimal controllers (Hovd & Skogestad, 1992, 1994). Similar results have been derived from the perspective of spatially invariant systems (Bamieh, Paganini, & Dahleh, 2002). While results in these areas are of significant theoretical interest and industrial application, such models adequately describe a very restrictive form of *sheet and film* process.

A weakness of the linear control approaches is that constraints can be satisfied only by sufficiently penalizing the control action in the objective function. Unfortunately, this will make the control action sluggish when the disturbances are uniform across the sheet/film and the control penalty is not needed. Another weakness is that these controller design methods do not explicitly address the issue of robustness to inaccuracies in the model. Because of this, applications of these methods can result in poor closed-loop performance (Featherstone & Braatz, 1997).

3.2. Linear control with antiwindup compensation

The traditional approach for dealing with constraints is to use simple static nonlinear elements (for example, selectors and overrides) which modify the linear control system only when necessary (Buckley, 1971a,b). Such methods are commonly referred to as antiwindup or antireset windup compensation (Fertik & Ross, 1967; Glattfelder & Schaufelberger, 1983; Peng, Vrancic, & Hanus, 1996). Two advantages of this approach are that: (1) well-developed linear control methods can be applied to design the linear controller; and (2) such constraint-handling methods are almost as easy to implement as a purely linear controller. The static nonlinear elements are simple operations requiring very little computational effort and are already standard in industrial control.

The disadvantages of using static nonlinear elements are that they can cause severe performance degradation such as limit cycles and increased variance (Bialkowski, 1988). Numerous ad hoc design methods have been developed for avoiding some of these problems, but these techniques can perform poorly (or may even lead to instability) in some situations (Campo, 1990). Optimization-based algorithms to construct antiwindup compensators have been proposed (Kothare & Morari, 1997), but are not yet sufficiently developed to consider for application to large-dimension processes. In fact, even the development of a nonconservative performance objective to use in such optimization-based algorithms while having reasonable computational requirements is a challenge (Rios-Patron & Braatz, 1998). Below we focus on three antiwindup approaches that have been discussed with respect to sheet and film processes.

Directionality compensation: Fig. 4 illustrates the method of handling constraints referred to as *directionality compensation* (Campo, 1990). When the output of the linear controller cannot satisfy the constraints on the actuator movements, the directionality compensator scales back the linear control output while keeping the same direction until the control action becomes feasible. For some industrial-scale adhesive coaters at Avery-Dennison, directionality compensation performed nearly as well as MPC (Braatz et al., 1992a). However, this is not expected to hold for general sheet and film processes.

Observer-based compensation: The use of observer-based antiwindup compensation (Åström & Wittenmark, 1984) was applied in a paper machine simulation study (Kristinsson & Dumont, 1996). While this approach is not optimal over the class of antiwindup compensators (Kothare, Campo, Morari, & Nett, 1994), its performance can be adequate for some processes.

Internal model control (*IMC*)*-based antiwindup compensation*: The use of the IMC-based antiwindup compensation (Zheng, Kothare, & Morari, 1994) for application to sheet and film processes has been proposed (VanAntwerp & Braatz, 1999b). This approach, which can be interpreted as an extension to model state feedback (Mhatre & Brosilow, 1996), optimizes a particular nonlinear time-domain performance objective. Although the method may not be optimal for the performance objectives most appropriate for a sheet and film process, a significant advantage to IMC-based antiwindup compensation is that it is rather simple to implement. It would be interesting to determine how well the approach works on realistic simulation models of large-dimension sheet and film processes.

Recently an antiwindup-based MIMO compensator for sheet and film processes has been proposed (Rojas, Goodwin, & Desbiens, 2002; Rojas, Goodwin, & Johnston, 2002). This approach is based on a real Fourier decomposition of the process interaction matrix and scales the control actions iteratively online so that the constraints are always satisfied. The method is stable under mild assumptions and has performance that, in simulation studies, is better than scaling or clipping, and near the optimal quadratic program (QP) solution.

3.3. Model predictive control

The application of MPC has been considered for the control of paper machines (Boyle, 1977; Dave, Willig, Kudva, Pekny, & Doyle, 1997; Doyle, Pekny, Dave, & Bose, 1997; Duncan & Corscadden, 1998; Rigopoulos & Arkun, 1996a; Rigopoulos, Arkun, & Kayihan, 1997d; Zheng, 1999), coating processes (Braatz et al., 1992a, 1992b), and polymer film extruders (Campbell & Rawlings, 1996b, 1998; Heath, 1996; Rawlings & Chien, 1993; Wellstead, Heath, & Kjaer, 1996). In MPC (Boyle, 1977; Eaton & Rawlings, 1992; Garcia, Prett, & Morari, 1989; Morari & Lee, 1991; Ricker, 1990) (and its many variants, MPHC (Richalet, Rault, Testud, & Papon, 1978), GPC (Clarke, Mohtadi, & Tuffs, 1987a,b, Tsang & Clarke, 1988), DMC (Cutler, 1982; Cutler & Ramaker, 1979; Morshedi, Cutler, & Skrovanek, 1985; Prett & Garcia, 1988), IDCOM (Fisher, 1991; Richalet, 1993; Richalet et al., 1978), MMC (Chia & Brosilow, 1991)), the control objective is optimized on-line subject to the constraints. A linear or quadratic optimization is solved at each sampling instance, and off-the-shelf software is available for performing these calculations for small-scale control problems (Morari et al., 1995). However, these optimization problems can be very large (over 500 decision variables and over 2000 constraints (Braatz, 1994; Rao, Campbell, Rawlings, & Wright, 1997; VanAntwerp & Braatz, 2000a)). For high-speed sheet and film processes with industrial control systems, it is not always feasible to solve the optimization problem within the sampling interval (Bialkowski, 1988; Braatz et al., 1992a; Dumont, 1990; Heaven et al., 1994; Kan, 1987; Young et al., 1986).

Consequently, algorithms have been developed that reduce the computation associated with obtaining an optimal or suboptimal solution to the linear program (LP) or QP associated with MPC. Much of this work was focused on application to sheet and film processes, although many of the algorithms that were developed apply to more general processes (Cannon & Kouvaritakis, 1998, 2003; Rossiter, Kouvaritakis, & Cannon, 2002).

Solving an MPC problem is equivalent to solving an LP or QP of size mn, where m is the control horizon (typically on the order of 10 sampling times) and n is the number of decision variables (usually equal to the number of actuators). An LP results if the objective is to minimize the 1-norm or ∞-norm of the measured sheet or film profile, and a QP results if the objective is to minimize the variance of the sheet or film measurements. The number of flops required by the fastest generic QP algorithms is $O((mn)^3)$ (Nesterov & Nemirovskii, 1994).

The computational requirements can be reduced for QP-based MPC algorithms using warm starts, sparseness, and blocking (Gelormino & Ricker, 1994; Ricker, 1990). Furthermore, the QP can be structured so that the computation time is linear in the control horizon m, giving a flop count of $\mathrm{O}(m(n+2p)^3)$, where p is the number of states (Rao et al., 1997). Warm starts, exploiting sparseness, and blocking can also be used with the LP formulation of MPC (Dave, Doyle, & Pekny, 1999; Dave et al., 1997; Doyle et al., 1997; Duncan & Corscadden, 1996, 1998; Duncan, Corscadden, & Heath, 1994). There has been some discussion concerning whether the LP or QP formulation is best suited to addressing the real control objectives in sheet and film processes (Castro-Velez, Doyle III, Meadows, & Saffer II, 1999; Pearson, 1976; Rao & Rawlings, 1998).

One approach to obtain faster computation times is to write the control vector in terms of a linear combination of a low number of basis functions, and then optimize over the coefficients of the basis functions. The lower number of optimization variables in the MPC algorithm results in shorter computation times. This approach has been demonstrated in simulations of a paper machine where the Karhunen–Loève (KL) expansion and the singular value decomposition (SVD) was used to define the basis functions (Rigopoulos, 1999, Rigopoulos & Arkun, 2003, Rigopoulos, Arkun, & Kayihan, 1997b). This latter reference used basis function expansions for the manipulated variables, the measured profiles, and the disturbances. It is possible to formulate an MPC algorithm so that the number of independent variables in the optimization problem is equal to the number of basis functions used to represent the disturbances, which can be much smaller than the number of basis functions used to represent the interaction matrix (Rigopoulos et al., 1997b).

Even faster computation times are possible using algorithms that compute an approximate solution to the MPC problem. The simplest approach is to add a penalty on the constraints in the objective function to an unconstrained MPC problem, and then iterate the penalty until the solution to the unconstrained MPC problem satisfies the constraints (Chen, Snyder, & Wilhelm, 1986; Chen & Wilhelm, 1986; Duncan, Dumont, & Gorinevsky, 1999; Halouskova et al., 1993; Wilhelm & Fjeld, 1983). A related approach speeds up the MPC computations by replacing the actuator constraints with an optimal 2-norm approximation (Braatz & VanAntwerp, 1997; VanAntwerp & Braatz, 1999a, 2000a, 2000b). This latter algorithm is robust in the sense that it avoids exciting uncontrollable process directions, although it does not actually guarantee robustness to all common types of model uncertainties. When implemented correctly these algorithms have an on-line flop count of $\mathrm{O}((mn)^2)$, and tend to provide a smoother series of input vectors than other methods. This can be an advantage in many practical applications for which a “sawtooth” input vector is undesirable (e.g., it may result in excessive wear to a slice lip). Another way to speed up MPC computations is to treat all future actuator settings as unconstrained (Zheng, 1999), which reduces the flop count to $\mathrm{O}(n^3)$. The loss in closed-loop performance using this approximation was negligible when applied to a simplified paper machine model and numerous other simulation examples (Zheng, 1999). Although in theory the approximate algorithms can result in poorer closed-loop performance, this loss in performance was observed to be negligible for some specific sheet and film processes.

The combination of time-varying Kalman filtering for profile estimation and the appropriate implementation of MPC gives nominally stable closed-loop dynamics (Campbell & Rawlings, 1995). A disadvantage of MPC is that no effective method exists for analyzing the closed-loop stability or performance under plant/model mismatch (Campo & Morari, 1987; Finn, Wahlberg, & Ydstie, 1993; Ordys, 1993; Prett & Garcia, 1988). Algorithms exist which guarantee zero steady-state error under plant/model mismatch for exponentially decaying disturbances (Polak & Yang, 1993; Zheng & Morari, 1993), but these algorithms provide no indication of the *dynamic* performance. Zafiriou (1990), Zafiriou and Marchal (1991) proposed a method for analyzing the dynamic performance for an uncertain linear system controlled by MPC, which was later extended by many authors, but the method is too computationally demanding to be applied to sheet and film processes.

Interestingly, control systems for sheet and film processes have been reported which provided adequate closed-loop performance with no or mild constraint-handling capabilities. For example, for an industrial-scale adhesive coater, it was shown that MPC did not provide an appreciable improvement in performance over a scheme which required much reduced computation (Braatz et al., 1992a). For a blown film extruder, a controller designed not to manipulate uncontrollable plant directions did not need constraint handling at all to achieve the desired closed-loop performance (Featherstone & Braatz, 1997). It was suggested that explicit constraint handling is not necessary for many large-dimension sheet and film processes provided that the controller is designed to be robust to model uncertainties.

Explicit conditions have been developed to determine whether constraint handling is needed for a particular process (Ma, VanAntwerp, Hovd, & Braatz, 2002; VanAntwerp, Ma, & Braatz, 2000). The formulation considers the effects of measurement noise, process disturbances, model uncertainties, plant directionality, and the quantity of experimental data. If the process disturbances are expected to be relatively small, then the constraints are less likely to be active than if the disturbances are likely to be relatively large. If the process model is highly uncertain, then the control actions for a robust controller will be small, resulting in constraints that are inactive. Application to a paper machine model constructed from industrial data suggests that many sheet and film process models are not sufficiently accurate to require explicit constraint handling, e.g., as offered by MPC. Nevertheless, an MPC or MPC-like algorithm may be preferred because constraints could be used to selectively zero out actuator moves when actuators break.

3.4. Robust control

Models for sheet and film processes have a significant amount of uncertainty associated with them (see Section 2.4). For large-dimension systems, simulation studies that plot deviations in the closed-loop response when the plant is perturbed provide a limited investigation of the robustness to model uncertainty (Braatz et al., 1992a; Campbell & Rawlings, 1996a; Dave et al., 1997). Recent studies investigated the extent to which model uncertainty limits closed-loop performance (Wills & Heath, 2002).

The function, μ, is a nonconservative measure for system robustness to model uncertainty (Doyle, 1982; Safonov, 1982). The strategy of *robust control* in addressing this plant/model mismatch is to represent the true process by a *set of plants*. The term *robust* is used to indicate that some property (for example, stability or performance) holds for a set of possible plants as defined by the uncertainty description. The term *nominal* refers to the system without model uncertainty. A detailed description of model uncertainty representation is beyond the scope of this paper and can be found elsewhere (Lundstrom & Skogestad, 1990).

No researcher has ever proposed the use of μ theory to design controllers for sheet and film processes without first reducing the dimension of the process. In fact, the computation time for *any* exact algorithm for μ theory will be exhorbitant for processes of high dimension (Braatz & Russell, 1999; Braatz, Young, Doyle, & Morari, 1994; Toker & Ozbay, 1995), no matter how cleverly the algorithm is constructed (Gunawan, Russell, & Braatz, 2001; VanAntwerp & Braatz, 2000c; VanAntwerp, Braatz, & Sahinidis, 1997, 1999). Although tight approximations allow computation which has polynomial growth as a function of process dimension, the order of this polynomial seems to be large ($\sim n^4$ for controller synthesis) (Boyd, El Ghaoui, Feron, & Balakrishnan, 1994; Young, Newlin, & Doyle, 1991). Published examples (Hovd et al., 1993; Laughlin et al., 1993) illustrate that current μ software (without dimensional reduction) is inadequate for sheet and film processes.

Several researchers have focused on reducing the computational load associated with designing, analyzing, and implementing robust controllers for sheet and film processes. One of the earliest studies of robustness of CD control systems was for shape control in steel rolling (Grimble & Fotakis, 1982). The robustness of several control schemes were compared through some analysis and in simulations. It was demonstrated that the use of basis function expansions could reduce the sensitivity of the closed-loop system to uncertainties in the interaction matrix. This theme was explored in a series of papers by various authors (Arkun & Kayihan, 1998; Duncan et al., 1998; Featherstone & Braatz, 1995; Featherstone & Braatz, 1998b; Featherstone & Braatz, 1999; Halouskova et al., 1993; Heath, 1996; Kristinsson & Dumont, 1993; Ringwood, 1993; Ringwood, 1995; Ringwood, 2000; Ringwood, Owens, & Grimble, 1990; Ringwood et al., 1994; Wellstead, Heath, & Kjaer, 1998). It has been shown that spline-based methods result in reduced order controllers that are less robust than those produced using other basis functions (Corscadden & Duncan, 1997c).

Laughlin et al. (1993) used circulant matrix theory to develop methods for designing conservative robust multivariable controllers based on the design of only *one* single loop controller. Circulant symmetric, Toeplitz symmetric, and centrosymmetric symmetric models were all covered by the theory. The controllers for circulant symmetric and Toeplitz symmetric models were decentralized; whereas centrosymmetric symmetric models were controlled by a decentralized controller in series with a constant decoupler matrix. A strong advantage of the approach was that no iterative design procedure (for example, like that required for DK iteration (Doyle, 1995)) was required for computing the robust controller. Disadvantages of this approach are that: (i) only parametric uncertainties in the interaction matrices are allowed; (ii) forcing the controllers to have these particular structures restricts the performance that can be achieved by the control algorithms; and (iii) application of the method to a process with a different number of sensors than actuators would require squaring-up to give a square transfer function matrix. Although squaring-up procedures have been applied industrially for at least the last 15 years (Grimble & Fotakis, 1982; Ringwood & Grimble, 1986; Ringwood & Grimble, 1990; Stewart, Gorinevsky, & Dumont, 1998b; Stewart et al., 2003a), they can result in a loss of performance when model uncertainty is taken into account (Corscadden & Duncan, 1997c; Russell & Braatz, 2002).

Duncan (1995) developed a robust controller design algorithm for sheet and film processes with arbitrary interaction matrices. Sufficient conditions for robust performance with multiplicative input and output uncertainties were derived in terms of satisfying robust performance for single-input single-output (SISO) subsystems. A scalar penalty on the manipulated variables was selected large enough for the resulting linear quadratic optimal controller to be robust. A similar approach was developed which provided robustness to a very highly structured uncertainty description by the setting of multiple control penalties (Stewart et al., 1998b). The algorithm was tested in simulations to a paper machine model constructed from experimental data.

Hovd, Braatz, and Skogestad (HBS) (Hovd, Braatz, & Skogestad, 1994; Hovd, Braatz, & Skogestad, 1996) used the properties of unitary-invariant norms to design nonconservative robust multivariable controllers based on controller synthesis for a diagonal plant. This method was applicable to circulant symmetric processes (i.e., no edge effects) for some types of uncertainty descriptions, and to general interaction matrices for other types of uncertainty descriptions. The approach was generalized to processes that have both controllable and uncontrollable modes (Featherstone & Braatz, 1995; Featherstone & Braatz, 1998c; Russell & Braatz, 1998). A modified version of the control algorithm (Stewart, Gorinevsky, & Dumont, 1998a) was implemented as an industrial CD controller working with a hardware-in-the-loop paper machine simulator (Stewart et al., 1999). The closed-loop performance results agreed with predictions from the robustness analysis.

The robust control algorithms of HBS were subsequently extended and refined (Featherstone et al., 2000; VanAntwerp, Featherstone, & Braatz, 2001). First, substantially simplified statements have been provided of both the theory and the resulting algorithms. Second, for many uncertainty types, the control design calculations have been further simplified. For example, where HBS may reduce the multivariable robust control problem to a large number of SISO robust control problems, in

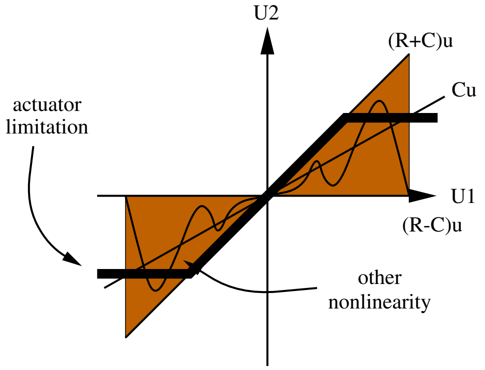

Fig. 5. Conic sector bounded nonlinearities (conic sector is shaded).

many cases it is possible to reduce the multivariable problem to a *single* SISO robust control problem. Third, nonlinear perturbations as shown in Fig. 5 as well as linear perturbations are addressed. The advantage of considering nonlinear perturbations is that some profile properties (such as moisture) provide nonlinear deviations from the nominal model. The extended algorithms are applied to a simulated paper machine, based on a realistic description of the interactions across the machine, and the level of model inaccuracies. This simulated example was of substantially higher dimensionality than that of any robust control problem ever considered.

3.5. *Profile estimation*

The CD profile must be determined from measurements taken either from traversing or full-scan sensors. Common industrial practice is to either take the current estimate at each sensor position to be its previously measured value, or a weighted sum of its previously measured values (Wang et al., 1993a). Since process disturbances are expected to be correlated (for example, during drying, heating, stretching), these methods may give poor profile estimates (Bergh & MacGregor, 1987b).

Several researchers have applied least-squares optimal estimation theory (Åström, 1970) to estimate the CD profile. For a process with a scanning sensor, profile estimates can be obtained using a periodic time-varying Kalman filter, which can be computed using a periodic Riccati difference equation (Bergh & MacGregor, 1987b; Campbell & Rawlings, 1995; Goodwin et al., 1994; Halouskova et al., 1993; Rawlings & Chien, 1996). An alternative approach to computing this Kalman filter is by solving a "lifted" algebraic Riccati equation (Tyler & Morari, 1995). A time-varying Kalman filter has been also derived for estimating the MD and CD variations for the case where there is both scanning and fixed sensors (Duncan, 1994b). Optimal least-squares estimation using a two-dimensional transfer function (the CD and the MD) has been explored in a series of papers (Heath & Wellstead, 1995a,b; Pinto & Wellstead, 1985). A scheme consisting of a recursive least-squares algorithm for estimating the CD profile deviations and an extended Kalman filter for estimating the MD deviations was developed (Dumont et al., 1991, 1993; Wang et al., 1993a,b). A dual Kalman filter which contains a combination of a temporal model and a spatial model has been applied to industrial processes (Chen, 1988). Wavelets can be used to greatly reduce the amount of data before feeding it into an estimation algorithm (Ahmadi, Dumont, & Ghofraniha, 1998; Nesic, Davies, & Dumont, 1996).

An alternative approach is to simultaneously estimate the profile deviations for a set of consecutive profile measurements (Rigopoulos, 1995; Rigopoulos, Arkun, & Kayihan, 1996). These profiles form a matrix, with the CD position as one index and MD position (or time) as the other index. Computing the SVD of the matrix and dropping subspaces associated with small singular values give a low-rank matrix in which random variability in the data has been smoothed. At each sampling time, the most recent profile measurement vector is included and the oldest profile measurement vector is dropped (Rigopoulos, Arkun, & Kayihan, 1997a; Rigopoulos, Arkun, Kayihan, & Hanczyc, 1996). This approach is closely related to principal component analysis, with the representation of the matrix in terms of the singular vectors also known as the KL expansion. The coefficients of the KL expansion can be modeled by a low-order autoregressive model (Rigopoulos & Arkun, 1996b, 2003; Rigopoulos, Arkun, & Kayihan, 1997c). The low-order representation for the profile deviations can be coupled with optimal control algorithms (Arkun & Kayihan, 1998).

Most sheet and film processes have nonuniform stretching or shrinkage, and sideways drift in the position of the sheet/film. This effect is usually large enough that it is not known a priori which sensor measurement locations correspond to which actuators. The estimation of these correspondences is usually referred to as the *mapping*, *lane identification*, or *alignment problem* (Duncan, 1989). The industrial standard approach to alignment is to perform some bump tests at various CD locations (Gorinevsky & Gheorghe, 2003), and then to use least squares with a known actuator response model (Duncan, 1997) to fit parameters that define alignment. The simplest model is the uniform shrinkage model, which assumes that the center of the downstream response c_j to the jth actuator is linearly related to the position of the jth actuator x_j (Gorinevsky, Heaven, Lynch, & Hagart-Alexander, 1995; Gorinevsky, Heaven, Sung, & Kean, 1997; Heaven, Gorinevsky, Kean, & Sung, 1998):

$$c_j = \alpha_1 + \alpha_2 x_j. \tag{1}$$

Alignment models for sheet and film processes with nonlinear shrinkage include fuzzy logic models (Gorinevsky, Heaven, Hagart-Alexander, Kean, & Morgan, 1997) and neural network models (Corscadden & Duncan, 1996). A technique to estimate the alignment using closed-loop data has been developed (Corscadden & Duncan, 1997b; Duncan, 1996; Gorinevsky & Gheorghe, 2003). The above alignment algorithms have been implemented on real machines (Corscadden & Duncan, 1997a; Gorinevsky et al., 1997; Gorinevsky & Gheorghe, 2003).

A measurement approach that may vastly improve the ability to construct the mapping for paper machines is on-line imaging and image analysis (Di Mauro, Wadhams, & Wellstead, 1994; Goiricelaya & Igarza, 1996; Guesalaga, Foessel, Kropholler, & Rodriguez, 1994; I'Anson, Wadhams, James, & Kropholler, 1990). The approach takes into account the fact that paper usually has a faint impression in it from the textiles used on the machine. While these faint impressions are not always visible to the naked eye, the impressions can be observed by image analysis algorithms that take into account the periodic nature of the impressions (such as Fourier transform analysis). This approach has been demonstrated in several applications to industrial paper machines (Wadhams et al., 1991). As computers become faster, the high-speed capture and processing of images will become more and more accessible, likely to the point where the results of the image analysis can be used in on-line control.

Another approach that may lead to improved profile estimates for Fourdrinier paper machines is the use of a CCD camera to measure the dry line, which is the visual border between where the fiber sheet has a glossy surface and where it has a rough surface (Kjaer et al., 1996, 1997). The glossy surface arises because of free-standing water at the surface of the fiber sheet, and the dry line occurs where the water has sufficiently drained through the Fourdrinier wire such that fibers are at the surface of the fiber sheet. The advantage of measuring the dry line is that these measurements can be collected much closer to the actuation than for traditional sensor technologies, resulting in a much shorter time delay. Also, the data can be collected at a much higher resolution than that obtained by scanning sensors. This sensor technology has been implemented on industrial paper machines (Kjaer et al., 1996, 1997).

3.6. *Model identification*

Usually the most challenging, time-consuming, and expensive step in the design of the control system is the development of the process model. The identification of accurate models for sheet and film processes is especially challenging when traversing sensors are used, since in this case the quantity of data is low relative to the dimensionality of the process.

However, the use of traversing sensors does not require a significant increase in the complexity of the development of model identification algorithms. The data can be utilized in a model identification algorithm, immediately after each sensor reading is taken, by using techniques developed for identifying process models when there are missing data (Bergh & MacGregor, 1987b; Jones, 1980; Ismail et al., 2003). It is straightforward to couple such techniques with any model identification algorithm which assumes that all data are available. Higher quality models are obtained when full-scan sensors are used (Chen & Subbarayan, 1999, 2002; Chen et al., 1998; Kristinsson & Chen, 1997), since the quantity of data provided by these sensors is many orders of magnitude larger than that provided by traversing sensors.

For most sheet and film processes, the high dimensionality and the strong interactions make it impossible to identify a highly accurate full-dimensional model between the actuator and sensor locations (Featherstone & Braatz, 1995; Kristinsson & Dumont, 1996). This motivates the identification of lower dimensional models, for example, as represented by orthogonal polynomials (Kjaer, Heath, & Wellstead, 1995; Kristinsson & Dumont, 1996; Wellstead et al., 1996), Fourier series (Duncan, 1989; Duncan & Bryant, 1997; Featherstone & Braatz, 1995; Stewart et al., 2003a), eigenvectors (Duncan, Heath, Halouskova, & Karny, 1996; Featherstone & Braatz, 1998c), wavelets (Zhihuan, Ping, & Yiming, 1999, 2001), or splines (Halouskova et al., 1993). The lower dimensional models can be either constructed directly from plant data, or by first constructing a full-dimensional model and then doing model reduction (Kristinsson & Dumont, 1996). The advantage of the second approach is that any known structure of the interaction matrix (e.g., Toeplitz) can be used in the construction of the full-dimensional model. This can greatly reduce the number of estimated model parameters, leading to better identifiability (Campbell & Rawlings, 1996b; Chen et al., 1986). Even fewer model parameters can be obtained if the response to a single actuator move can be parametrized with a small number of model parameters (Duncan et al., 2000; Ghofraniha, Davies, & Dumont, 1995a,b). Such approaches have been applied to industrial data (Ghofraniha, Davies, & Dumont, 1997; Stewart et al., 2003a).

The poorly conditioned nature of sheet and film processes motivates the identification of both a nominal model and an estimate of its accuracy. This accuracy estimate should be nonconservative, otherwise the resulting closed-loop performance obtained by a robust controller will be sluggish. On the other hand, too tight of an uncertainty description will lead to aggressive control actions with large overshoots or possible instability. Linearized statistics (Beck & Arnold, 1977) or Monte Carlo simulation (Beckenbach, 1956) can be used to produce nonconservative estimates of the model accuracy (Featherstone & Braatz, 1997, 1998b). Then the model uncertainty description can be used to determine the order of the lower order model for the interactions. The limitations of using a lower order model on closed-loop control have been quantified (Wills & Heath, 2002). These measures could be used to gauge whether or not it is worthwhile to more accurately identify the process model.

A significant consideration for poorly conditioned processes such as sheet and film processes is the experimental input design. The industrial standard is the “bump test”, in which the output data are collected for a simultaneous step input in a limited number of actuators across the machine (Gorinevsky & Heaven, 1997; Gorinevsky et al., 1996; Gorinevsky & Gheorghe, 2003). A more sophisticated approach that has been applied to an industrial paper machine is to use pseudo-random binary sequences instead of step inputs at the limited actuator locations (Heaven et al., 1996). Neither of these experiments excite the higher order spatial modes (Featherstone & Braatz, 1998a), so the resulting input–output data are not sufficiently informative to construct accurate models for those modes. An alternative approach is to move all the manipulated variables simultaneously (Chen & Subbarayan, 1999, 2002). While such an approach may give more informative data than moving a limited number of actuators, it still provides lower signal-to-noise ratios in plant directions associated with higher order spatial modes (Featherstone & Braatz, 1998a).

A systematic procedure has been developed for selecting the manipulating variables during the collection of input–output data to simultaneously satisfy process constraints and to provide the most useful model information for closed-loop control purposes (Featherstone & Braatz, 1998a; Featherstone et al., 2000). The procedure involves the solution of a nonlinear program with the process constraints as program constraints and the objective a function of the process modes. The procedure leads to order-of-magnitude improvements in model accuracy, and significant improvements in closed-loop performance. A further advantage of this approach is that the number of experiments needed to build a highly accurate model is much less than with other approaches.

3.7. *On-line process monitoring*

On-line process monitoring includes the problems of fault and failure detection, isolation, and compensation. In what follows we will use the term *fault* to apply to both faults and failures, since a *failure* is just an extreme type of fault.

Fault detection: The detection of faults during paper machine operation has been explored by many researchers. The predominant approach is to calculate on-line the sheet or film profile variation (Burns, 1974; Dahlin, 1970; Richards, 1982; Wilhelm & Fjeld, 1983) or other statistics (DeVries, Pandit, & Wu, 1977; DeVries & Wu, 1978; Kayihan, 1997, 1999) from the process input–output data. An increase in a statistic indicates that a fault has occurred (Himmelblau, 1978; Kaspar & Ray, 1992; Kozub & Garcia, 1993; Russell, Chiang, & Braatz, 2000).

Fault isolation: It is common to isolate the direction of faults by separating the overall profile variance (σ^2) into CD (σ_{C}^2), MD (σ_{M}^2), and residual (σ_{R}^2) components (Burns, 1974; Dahlin, 1970; Smook, 1992). The typical assumption is that the components of the total variation are independent, so that the total variance is the sum of its components: $\sigma^2 = \sigma_{\mathrm{C}}^2 + \sigma_{\mathrm{M}}^2 + \sigma_{\mathrm{R}}^2$. This assumption, although not applicable for many process disturbances (Richards, 1982), allows the separate calculation of the variances (Burns, 1974; Cutshall, 1990; Wilhelm & Fjeld, 1983). An increase in either directional variance (σ_{C}^2 or σ_{M}^2) indicates that the fault is along that direction. An increase in the residual variation σ_{R}^2 may indicate that the fault is due to a sheet or film instability (Burns, 1974; Sartor, 1990; Wilhelm & Fjeld, 1983).

An approach that takes into account system controllability has been developed (Allwood & Duncan, 1996; Duncan et al., 1999; Duncan, Dumont, & Gorinevsky, 2000), in which the variance of the observed profile is compared to that obtainable by a minimum variance controller. Both variances are computed only over the controllable subspace of the interaction matrix, since no control algorithm can be expected to reduce the variations for the uncontrollable modes of the process (Duncan et al., 1998; Duncan & Bryant, 1997; Featherstone & Braatz, 1995, 1997). The use of the process model in the fault detection procedure is a significant departure from earlier methods for detecting machine problems. The approach allows the isolation of faults. The difference between the observed profile and the minimum variance profile can be mapped back to the actuators to allow poor control to be associated with individual actuators (Duncan et al., 1999). Plotting the difference in variations associated with each actuator as a function of scan number provides a clear picture of the operating conditions of the machine. Application to data from an industrial paper machine allowed the quick determination of poor control associated with a number of actuators.

For applications in which the actuators have a substantial likelihood of becoming faulty, it is useful to feed back a direct measurement of the actuator location (Braatz et al., 1992a; Campbell & Rawlings, 1996b; Nuyan, 1986; Siler, 1984; Wahren, 1986). This allows quick detection of stripped screws, burned-out motors, etc. There is a strong need for isolating actuator faults in sheet and film applications where direct feedback is impractical or difficult.

Fault compensation: The controllers produced by the design procedure of Laughlin et al. (1993) were provably tolerant to actuator failures. Although several researchers (e.g., see Braatz, Morari, & Skogestad, 1994 and citations therein) have proposed methods to design linear controllers which are tolerant to faults for general processes, these methods are either computationally expensive or conservative. Also, a *different* linear controller is expected to be optimal for each operating condition associated with each fault. Therefore, requiring the fault compensator to be the *same* linear controller for all conditions may give very poor performance for some or all of the operating conditions. MPC, although computationally expensive, provides a simple *nonlinear* method for fault compensation for general processes—the fault is represented as an additional constraint in the QP or LP formulation (Prett & Garcia, 1988). This approach has been applied to a simulated polymer film extruder (Campbell & Rawlings, 1996b), where direct measurement of the actuator positions was used to locate a faulty actuator.

4. Conclusions and future directions

A significant amount of research has been conducted on sheet and film process control in the last few decades. This paper provided a description of how this research has addressed many of the important characteristics of these processes.

In the early work many different basis functions were proposed, Gram polynomials, Chebychev polynomials, splines, etc. Eventually the SVD of the process interaction matrix dominated the literature (the SVD decomposition reduces to a real Fourier decomposition in the case that the process matrix is circulant symmetric), and in industrial implementations of CD control (Stewart et al., 2003a; Stewart, Gorinevsky, & Dumont, 2003b). The most significant result of this early work was the recognition that the sign of the process gain in directions corresponding to the small singular values could not be known with certainty, and hence no attempt should be made to control those modes of the process. SVD controllers were constructed to decouple the process modes, and ensure that no attempt would be made to control uncontrollable modes. Controllers with this structure were proven to be optimal for a wide variety of model uncertainty types.

One of the early unknowns in sheet and film processes was that, for a long time, it was unclear how to best identify the independent modes of the process. Now it is clear that the independent modes of the process are combinations of actuator settings that correspond to pseudo-singular values of the process (also called the spatial frequencies for circulant symmetric processes). Robust control results that exploit the structure of sheet and film processes reveal which of these modes are independently controllable. The number of controllable modes can be much less than the number of actuators, and it varies from process to process. Quantitative tools were developed for computing which modes were controllable.

In recent years the CD control algorithms developed primarily by academia during the 1990s were successfully transferred into industrial practice (Stewart, Gorinevsky, & Dumont, 2003a,b). The current generation of CD control algorithms represents the largest scale (and one of the most successful) application of robust control theory in industry.

Although these methods have been successfully applied in industry, these still have a key limitation, which is that the methods are purely data based. It seems to the authors that the next step in improvement in closed-loop performance can be achieved only by incorporating the physics and chemistry of the process when constructing the model to be used for control purposes. Such first-principles models, which must be distributed parameter models to capture all of the relevant phenomena, have been available for metal rolling for many years (e.g., see Allwood, 1993 and references cited therein). The construction of such models for most other sheet and film processes is rather challenging, given the complexities of the phenomena, such as particle–particle interactions and turbulent fluid dynamics during paper machine operations, and crystallization and large and highly nonlinear viscosity variations during polymer film extrusion. Incomplete models for paper machines were published more than 10 years ago (Balakrishnan & McFarlan, 1985; Ghofraniha et al., 1995a; Laughlin et al., 1993). Much more progress has been made in the first-principles modeling of coating and polymer film extrusion processes (e.g., see Pirkle & Braatz, 2003, 2004 and references cited therein). Given the computational complexity of first-principles models for sheet and film processes, the goal for the purposes of CD control would be to utilize a deep understanding of the first-principles models to define parametrized low-order input–output models. If successful, such models would enable shorter identification experiments, which would lead to less wasted product. Such first-principles models also would be valuable for the design of the spatial characteristics of the actuators and the optimal position and spacing of sensors and actuators (El Jai & Pritchard, 1987).

There are several problems in sheet and film control that are still unresolved. When sheet and film processes change grades or thicknesses of product, typically a gain scheduling approach is applied. The new process model is identified online to set the new controller gain. The identification method typically used is to saturate a low number of selected inputs and measure the response. Another related problem that has not been adequately addressed is the lane identification problem, that is, identifying which actuators effect which measurements. As in modeling, the approaches that have been tried have taken a purely data-driven point of view. Better performance would be expected if physical insight was incorporated into the lane identification algorithms.

Structuring control algorithms to effectively handle multiple banks of sensors and actuators, which is common in paper machines or polymer film extruders, still needs more research attention (Haznedar & Arkun, 2002). Robust control and MPC algorithms have not been developed to nearly the same level of sophistication and completeness as for single sensor and actuator banks.

Acknowledgment

Funding is acknowledged from DuPont, International Paper, the Computational Science and Engineering program at the University of Illinois, and the Calvin College Board of Trustees.

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