Cross-Directional Control of a Paper Machine

Overview

The goal of this project is to expose you to a realistic industrial robust control problem - cross-directional (CD) control of a paper machine. The process models have been identified from industrial process data, and real world model uncertainty issues have been captured in the uncertainty sets.

Section 1 is a detailed description of CD control and is meant to provide motivation as well as to provide the context for the example systems in this project. Section 2 presents the process model structure in transfer matrix format. Also included is a description of the model uncertainty which is typical for each process. Section 3 describes the closed-loop specifications that are typically considered when designing an industrial CD controller. Finally, Section 4 presents some questions to be answered upon finishing the project.

1 Detailed Background[1]

A paper machine is used to transform a slurry of water and wood cellulose fibres into a saleable sheet of paper as efficiently as possible. The following description of its operation is very brief and more complete discussions of this complex process may be found in [4, 12]. Figure 1 illustrates the main parts of a typical configuration of a Fourdrinier style paper machine. The slurry enters the headbox at the left of the figure and the dry paper is wound up on a roll at the far right in the figure.

Wet pulp at about 0.5% consistency (0.5% fibres and 99.5% water) is pumped into the headbox of the paper machine. The job of the headbox is to distribute the slurry such that the fibres are evenly distributed over the wide flow area (up to 11m). The slurry is then deposited on to an endless wire mesh belt which may be moving at speeds in excess of 100km/h. The wet pulp is dewatered as water is lost through the mesh due to blades and suction boxes placed under the wire screen. The sheet, now composed of approximately 20% solids, is heated by steam boxes before and during the press section where it is pressed and dewatered between counter-rotating rollers. The sheet, now about 40% dry, then enters the dryer section and a series of steam heated dryer cans. The sheet of paper exiting the dryer section typically contains 5-9% water content by weight. The dry sheet then enters a series of rotating rollers known as the calendar stack where the sheet thickness, or caliper, is controlled. In paper production, the three most important properties of the finished product are (1) the sheet weight per unit area in terms of grams per square metre (gsm), (2) the sheet moisture content expressed as a percentage of the sheet weight (%), (3) the

[1] Reprinted with permission from Chapter 1 in[13].

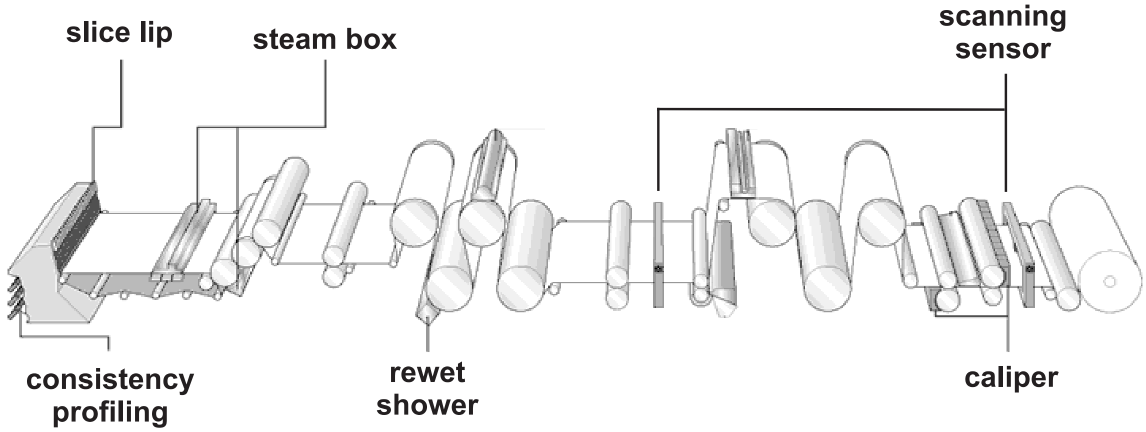

Figure 1: Wide view of the paper machine showing relative positions of the various actuator arrays and scanning sensor(s). (Artwork courtesy of Honeywell-Measurex.)

caliper or thickness of the sheet expressed here in μm. These properties are each measured by a scanning sensor which traverses back and forth across the moving paper sheet.

The quality of the paper sheet is defined in terms of the variance of these properties [1]. If a roll of paper is produced which is measured by the scanning sensor at m locations and the roll consists of T scans, then the sheet measurements are given by $x(i,j)$ where $i = 1, \ldots, m$ and $j = 1, \ldots, T$, and the average is given by,

$$\bar{x} := \sum_{i=1}^{m} \sum_{j=1}^{T} \frac{x(i,j)}{mT} \tag{1}$$

The variance of the two-dimensional measured paper sheet is known within the industry as 'two-sigma' and is defined by

$$2\sigma := 2 \cdot \sqrt{\sum_{i=1}^{m} \sum_{j=1}^{T} \frac{(x(i,j) - \bar{x})^2}{mT - 1}} \tag{2}$$

and is an important quality factor. Many control strategies have posed the CD control problem in terms of a minimization of (2) with the setpoint r substituted for the profile average $\bar{x}$ in (2).

In order to define the control problem, some definitions and orientation is required. The direction of sheet travel is known as the machine direction or MD and is from the left to right in Figure 1. The direction perpendicular to the sheet travel is known as the cross direction or CD. Due to the process design and nature of the actuators, the industrial approach to paper machine control considers the MD and the CD problems separately.

MD control is concerned with controlling the average value of each scan. The control of the dynamically varying, but zero-mean, error profile is known as CD control and is the task of arrays of actuators distributed across the width of the paper machine, as shown in Figure 1. However, as the sensor is scanning a moving sheet, it traces a diagonal path across the paper sheet, and thus it does not measure pure MD and CD paper profiles. Filtering of the sensor signal is used to aid in the separation of the MD and CD components.

The majority of industrial paper machines possess at least one CD actuator array for each of the three main paper properties. The most common CD control techniques are outlined below.

1.1 Basis Weight Control

The weight per unit area of a sheet of paper, is an important factor in the quality of the finished product, the metric measurement is grams per square metre (gsm). Variations in the weight of the paper sheet will affect most other properties [4]. A sheet of newsprint has a weight of about 45gsm, a paperback book cover may have a weight of about 300gsm, and cardboard may weigh 450gsm.

CD control of the weight of a paper sheet is accomplished by actuators at the headbox (Figure 1). The job of weight control actuators is to achieve an even distribution of the pulp fibres across the width of the wire belt, despite changing pulp properties. Since the weight control actuators are located the furthest upstream, the dynamics of weight control often require the consideration of a significant dead time component, as the paper sheet must travel through the entire machine before reaching the scanning sensor.

Since the raw material used is wood, it happens that the pulp stock characteristics change over time. The consistency and drainage properties of the delivered stock are kept as constant as possible by the approach system, but variability inevitably occurs. In addition, the flow of the pulp stock through the headbox and on the wire belt can distribute the wood fibres unevenly in the cross-direction. Basis weight profile control is important not only for paper strength reasons, but also due to the fact that a poor quality weight profile will propagate downstream and appear as disturbances in both the moisture and caliper profiles.

The operation of the two most common weight control actuators is described next.

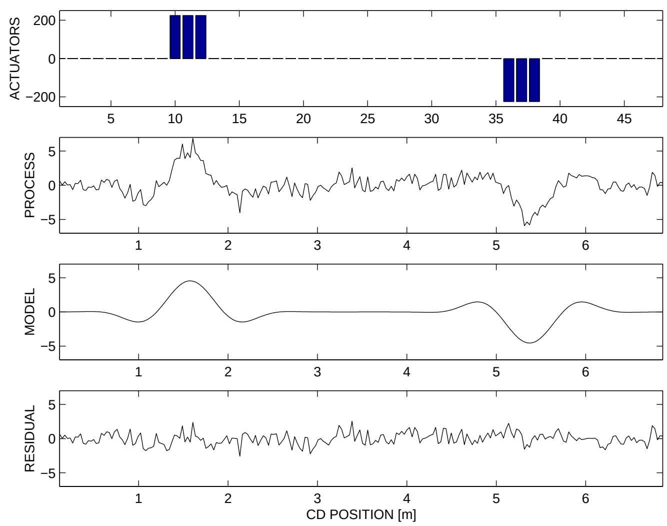

Figure 2: Steady-state response of basis weight to slice lip actuators on a heavy grade 200gsm linerboard machine. This is one of the wider weight responses in CD control. (Data courtesy of Honeywell-Measurex.)

1.1.1 Slice Lip

The use of a slice lip is the traditional method of controlling the CD profile of basis weight of a paper sheet. The slurry exits the headbox through an opening which is as wide as the paper machine (up to 11m) but only 1cm–2cm tall for fine paper and 4cm–6cm tall for linerboard. The amount of pulp exiting the headbox is controlled by locally changing the height of this opening by bending its flexible upper lip. A taller opening is used to allow more pulp on to the wire thus increasing the amount of fibres at that location and increasing the basis weight.

The bending of this upper lip is controlled by an array of force actuators distributed along its length. A typical slice lip installation has $n = 50$ of such actuators in the array, but there exist installations with $n = 118$ or more slice lip actuators. The actuator spacing is quite variable depending on the installation and is anywhere from 7.0cm to 20cm.

The response of the basis weight profile to the slice lip actuators varies widely. Moving a slice lip actuator in a 45gsm newsprint installation results in changing the weight profile only for a strip about as wide as the actuator zone itself. Heavy grade paper is altogether different. Bending the slice lip for a slow moving heavy weight paper process produces a very wide response with significant negative gain side lobes as shown in Figure 2. The response to a single actuator may cover over a third of the entire width of the paper machine.

The slice lip itself is quite expensive, and much care is taken to prevent damaging it due to excessive flexing and bending. Depending on the lip material, each actuator has a range of at most 0.17mm-0.75mm. The industrial controller contains many safety interlocks and an actuator setpoint profile is prevented from violating the bending constraints specified for the slice lip.

Modern slice lip actuator dynamics are very fast compared with the scan time. The process dynamics are thus dominated by the sensor filtering and the dead time due to the transport delay from the actuators to the scanning sensor.

1.1.2 Consistency Profiling

A newer method for basis weight control, known as consistency profiling or dilution control, is described in [14]. These actuators change the basis weight profile by locally altering the concentration of pulp fibres in the headbox. This is accomplished by an array of dilution actuators distributed across the back of the headbox. The consistency of the pulp stock is changed by injecting it with a stream of low consistency water as it enters the headbox. An increase in the flow of a dilution actuator reduces the local concentration of pulp fibres and thus locally reduces the resulting basis weight.

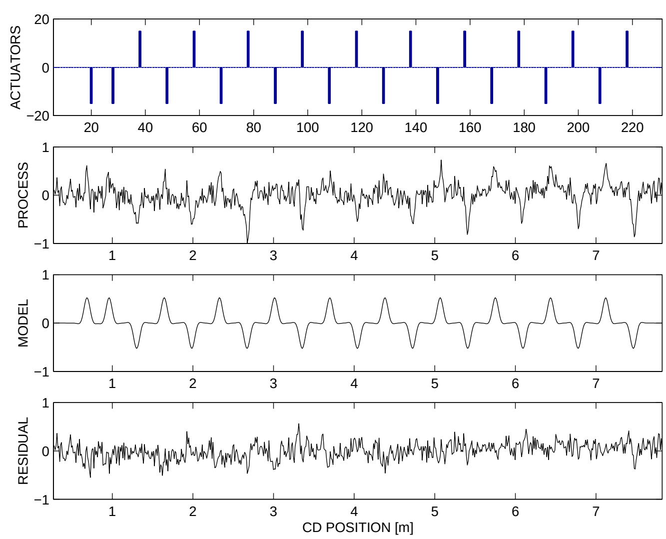

Figure 3: Steady-state response of basis weight to consistency profiling actuators on a 45gsm newsprint machine. (Data courtesy of Honeywell-Measurex.)

The industrial implementation of consistency profiling falls into several different configurations. One configuration typically has $n = 150 - 200$ actuators with up to $n = 298$ actuators installed on 3.5cm centres. A second configuration typically has $n = 60 - 80$ actuators installed on 6.0cm-7.0cm centres. Within the industry, there exist other consistency profiling systems with different configurations.

The response of the weight profile to a consistency profiling actuator is typically very well localized with none of the side lobes that may be observed in slice control, compare Figures 2 and 3. The typical effect of a consistency profiling actuator is confined to a 12.5cm strip centred on the actuator, and most of its influence being concentrated in the central 7.5cm.

As with the slice lip, the consistency profiling actuator dynamics are very fast compared with the scan time and the process dynamics are dominated by the sensor filtering and the transport delay.

1.2 Moisture Control

The moisture content of a sheet of paper is a very important factor in determining paper strength [4]. Typical moisture content targets are 5–9% of the total weight of the paper sheet. Overdrying a paper sheet will reduce its strength as the fibres are damaged. An excessively variable moisture profile leads to a variable temperature profile and thus increases the demand on the caliper profiling actuators.

The dewatering and drying of the paper sheet as it passes through the paper machine is very complex and is affected by many factors. The fibre slurry exiting the headbox is approximately 0.5% fibres and 99.5% water. The paper which is wound up on the reel is about 95% fibres and 5% water. This impressive feat is accomplished through a well designed process. The goal of feedback CD control of moisture is to perform the fine control and level a variable moisture profile.

Disturbances in the moisture profile may be introduced by a variety of sources. The cross-coupling of actuation between processes means that weight actuation appears in the measured moisture profile[1].

Steady-state or dynamically varying disturbances may be introduced by plugging of the mesh or uneven tension in the felt (the wire screen belt which is used to guide and support the newly-formed paper sheet), malfunctioning water drainage from dryer cans, or uneven suction from vacuum boxes placed across the sheet.

Analogous to the weight profile, an uncorrected moisture disturbance will propagate down-stream and appear in the caliper profiles.

1.2.1 Steam Boxes

Counter-intuitively the addition of steam to a wet paper sheet is used to help dry the sheet (see [11] and references therein). The steam-heated water in the wet paper sheet has a lower viscosity than cooler water and is more easily extracted from the paper sheet by the presses.

Industrial steam showers are implemented in an array of $n = 55$ actuators on average, and up to $n = 171$ in some wide paper machine installations. The actuator separation is between 7.5cm–15cm depending on the specific installation. The response of the paper sheet to the application of steam depends on many factors but its main lobe is typically between 30cm–60cm wide. The process also responds with smaller-amplitude side lobes, resulting in a total response width between 60cm–120cm wide, see Figure 4. A lighter weight paper sheet is more likely to have a narrower response, as the steam penetrates the thinner sheet more readily.

[1] This 'disturbance' may sometimes be used to our advantage. For example slice lip actuators are used to control the moisture profile in [2].

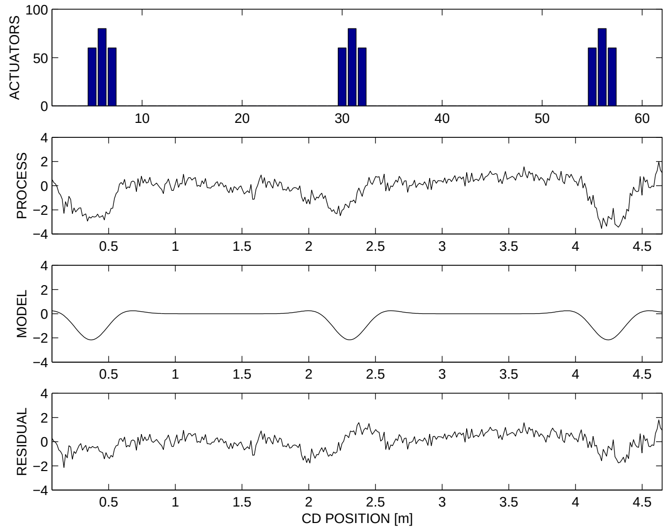

Figure 4: Steady-state response of moisture to steam box profiling actuators on a machine making 50gsm paper with 6% moisture target. (Data courtesy of Honeywell-Measurex.)

The steam box actuators are typically capable of providing up to 2% (or sometimes more) of the total sheet weight moisture content correction. The process response to steam box actuators is much slower than the pure time delay response dynamics of the basis weight actuators in Section 1.1. The response to the application of steam has a time constant around 200-250s. The paper sheet is in constant contact with many presses and rollers and the steam box must raise the temperature of all of these before the new equilibrium may be reached.

1.2.2 Rewet Shower

Dry streaks in a paper sheet can be corrected through the use of a remoisturizing spray or rewet shower. These actuators are used to fill in the dry spots in a paper profile by applying an atomized water spray directly to the sheet. Rewet showers may be used on machines producing almost any grade of paper.

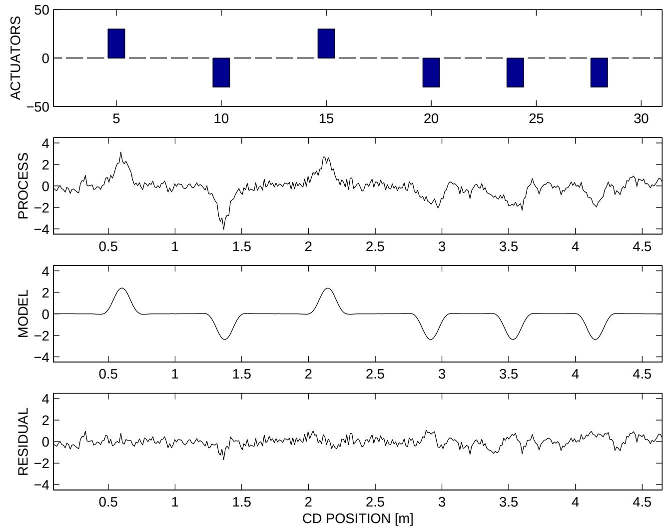

Figure 5: Steady-state response of moisture to rewet shower profiling actuators on a machine making 50gsm paper with 6% moisture target. (Data courtesy of Honeywell-Measurex.)

Industrial rewet showers are implemented in an array of $n = 50$ actuators on average, and up to $n = 120$ in some wide paper machine installations. The actuator separation is between 7cm-15cm and the typical response is confined to a 18cm strip centred on the actuator, with 80% of the water occurring in the central 15cm. Figure 5 illustrates a typical response.

Typically the rewet shower actuators are capable of providing 1-2% moisture content correction. The rewet shower can work on some light weight installations to provide up to 3-4% moisture content adjustment.

The dynamics of the rewet shower actuators are very fast compared with the scan time and the process dynamics are dominated by the sensor filtering and the transport delay.

1.3 Caliper Control

The caliper of a sheet of paper is controlled by feeding the paper sheet through rotating rollers, known as the calendar stack. The pressure that the rolls exert on the paper sheet may be adjusted by locally heating (cooling) one of the rollers. As the temperature of the roller increases (decreases), its diameter also increases (decreases) due to thermal expansion, and thus the pressure on the paper sheet increases (decreases), leading to a decrease (increase) in the paper caliper [9].

The earliest CD caliper control was implemented through the use of hot and cold air showers on the roller. Modern caliper control is much more efficient and uses induction heating actuators. A high frequency alternating current is used to generate an oscillating magnetic field at the roller surface. The resulting eddy currents near the surface of the roller cause the temperature of the roller to rise, and subsequently an increase in roller diameter.

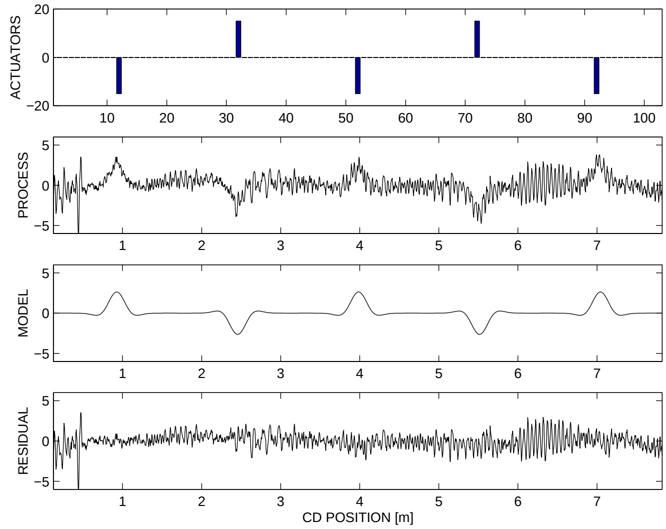

Figure 6: Steady-state response of caliper to induction heating profiling actuators on a machine making newsprint with 78μm caliper target. (Data courtesy of Honeywell-Measurex.)

Industrial caliper control is implemented in an array of $n = 100$ actuators on average, and up to $n = 150$ in some wide paper machine installations. The actuator separation is 7.5cm and the typical response has around 30cm–40cm wide main lobe and 10–15cm wide side lobes (Figure 6).

Caliper setpoint targets are typically in the range 70μm to 300μm depending on the grade. The induction heating actuators are capable of providing up to 10μm caliper profile correction. Induction heating is the slowest of the actuators considered here. The response of the caliper to the actuator setpoints varies from very slow to an almost integrating response. Typically this rise time is the dominant factor in the process dynamics. The dead time due to the transport delay of the paper sheet is usually quite small due to the scanning sensor often being installed just after the calendar stack (Figure 1).

Disturbances in the caliper profile can be caused by variation in the moisture profile. A wet streak in the paper causes the roll temperature (and hence compression on the paper) to decrease close to the streak.

Other caliper disturbances may be induced by the set-up of the calendar stack. An uneven pressure profile may be caused by uneven calendar stack loading or uneven roll diameter in the CD. This will appear as a steady-state disturbance in the measured caliper profile.

2 Modelling and Analysis

2.1 Nominal Process Model

The model is defined in discrete time (by abusing notation and mixing time domain and Z-transform domain) as,

$$y(t) = G(z) \cdot u(t), \tag{3}$$

where the array $y(t) \in \mathcal{R}^{m\times 1}$ represents the measured paper property, and typically there are $200 \leq m \leq 2000$ measurements taken across the width of a paper sheet. The array $u(t) \in \mathcal{R}^{n\times 1}$ represents the setpoints[2] of the actuators, and there are typically $30 \leq n \leq 250$ actuators on an industrial system.

The transfer matrix $G(z)$ in (3) is typically separated into a dynamical and spatial components,

$$G(z) = g(z) \cdot G \tag{4}$$

where the dynamics are described by the scalar transfer function,

$$g(z) = \frac{(1-a)z^{-d}}{1-az^{-1}} \tag{5}$$

where the integer d is used to represent the process time delay usually associated with the transport delay from the actuators to the scanning sensor (see Figure 1). The constant a is the discrete-time pole which represents the open-loop time constant of the system. In practice, the value of a is partly due to the dynamics of the process and partly due to the filtering associated with the sensor.

The spatial response is modelled by the constant real matrix

$$G \in \mathcal{R}^{m\times n} \tag{6}$$

where m is the number of measurements (typically 200–2000) taken across the sheet and n represents the number of actuators (typically 30–250). The matrix G in (6) is responsible for defining the response shapes illustrated in Figures 2–6 above. The modelling of a CD process often assumes that the paper sheet will respond to each actuator in the same way, only the response will be shifted accordingly. Roughly speaking, this corresponds to a matrix G in which each column contains the same 'bump response shape', but shifted to line up with the appropriate input actuator. Stated another way, the j^{th} column of G in (6) contains the predicted change in the steady-state response of the process to a unit step change in the j^{th} actuator.

From Figures 2–6 above, you will also notice that the effect of each actuator appears to be localized on the paper sheet. This may be observed by the large number of zero entries in the model G matrices in your data.

(If this description is hard to follow, then now would be a good time to open one of the MAT files and plot various columns of the G matrices.)

Although the dimension of $G(z)$ in (4) is quite large, the features mentioned above can lead to simplifications in controller design. The reference [8] may provide some ideas that could aid in designing a controller for a process that has been modelled with separable dynamics (such as $G(z)$ in equation (4)).

[2]The inputs are referred to as 'setpoints' due to the fact that for many cross-directional control actuators, an internal feedback loop is responsible for moving the actuator to the desired value. This internal loop is beyond the scope of your project.

2.2 Model Uncertainty

Section 2.1 discussed the nominal model of the control system. This section will now explore a few of the more common forms of model uncertainty that are encountered when modelling industrial CD control processes. Process models such as shown in Section 2.1 are typically obtained from the analysis of input/output data from a paper machine[3] It is sometimes difficult to model a response accurately from the noisy process data. In addition, a working mill typically identifies a process model only occasionally. Over the course of days and weeks the process may end up acting differently than it did at the time of the model identification.

1. Consistency profiling control of Newsprint (data in the file *consistency.mat*).

   Here we consider a paper machine which is using $n = 226$ consistency profiling actuators to control the basis weight of a sheet of newsprint measured at $m = 687$ locations across the machine. Typically a newsprint machine is well behaved, and is easily modelled and controlled in a working mill. However, an important issue in systems controlled with consistency profiling actuators is known as system *alignment*.

   In order to perform good CD control, one must know what region of the paper sheet is affected by a certain actuator. This is not always possible as the sheet may wander or shrink, leading to uncertainty in the position as illustrated in Figure 7. In a properly aligned paper machine, one is certain that the process model is correctly predicting where the response will occur. Once a system becomes mis-aligned, then the controller can cause the actuators to chase a disturbance that really 'belongs' to its neighbour. Once this happens, the control system can quickly go unstable.

   For this project we will be modelling the effects of sheet wander of ±3cm on a 7.9m wide paper machine.

   You will find a matrix H of dimension 693×226 in your data file.

   Now consider the 687×693 matrix in Matlab notation,

   $$E_\delta = [\text{zeros}(m, 3-\delta) \quad \text{eye}(m) \quad \text{zeros}(m, 3+\delta)], \tag{7}$$

   Then the family of models that describe the system with alignment uncertainty will be given by,

   $$\Pi_A : \qquad G_p = E_\delta \cdot H; \qquad \delta = -3, \ldots, 0, \ldots, +3 \tag{8}$$

   Rewrite this physical description of alignment uncertainty in a format appropriate for control system analysis and design. There are many potential structures (see Chapter 8 in your text for some examples). Defend your choice! Your choice of $M\Delta$ must include all members of the set Π_A in (8), but at the same time it should not be so large as to limit the performance of your subsequent controller design. Also, although the set Π_A in (8) is a very structured description, it is always good engineering practice to include some margin for uncertainty that may be outside the given set.

2. Slice lip control of linerboard (data in the file *linerboard.mat*).

   The results of a bump test and subsequent model identification on a linerboard machine produce results that are ambiguous. Judging from the noisy data, either of the two matrices G_1 or G_2 (or anything in between) seem to be likely choices for G in (3). After a very stressful

[3] More information on the model identification for CD processes may be found in [5, 6, 7].

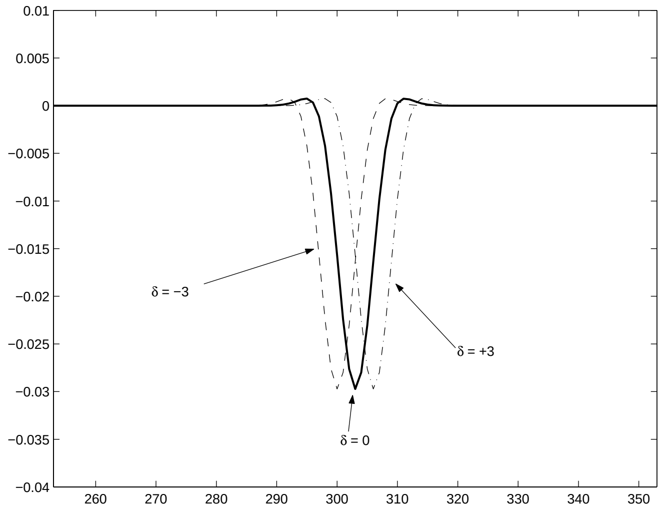

Figure 7: Responses of three different models G_p in (8) to a step change in the 100^{th} actuator (Data courtesy of Honeywell-Measurex.)

meeting (in which someone says "*Both* models are *obviously* valid. What's the problem?") you decide to go with the uncertainty structure:

$$\Pi_B : \qquad G_p = \lambda \cdot G_1 + (1 - \lambda) \cdot G_2 \; ; \qquad 0 \leq \lambda \leq 1 \tag{9}$$

Rewrite the physical description of model uncertainty in (9) in a format appropriate for control system analysis and design. There are many potential structures (see Chapter 8 in your text for some examples). Remember, it is a common approach to use unstructured uncertainty to 'cover' some structured uncertainty. As in process modelling, there is a trade-off between simplicity and fidelity in modelling your uncertainty as well. Defend your choice! I.e. show that all members of the set Π_B in (9) are included in your structure.

Analysis

Before jumping into the controller design, you should perform an open-loop analysis of these systems. Include any analysis techniques that you have learned that you think may be useful. Compute the SVD and comment on the condition numbers of the systems. Do you expect that these systems will be difficult to control? Make sure you include the results of the analysis in your report. Discuss how this analysis will affect your controller design approach.

3 Controller Design

Most off-the-shelf controller design packages will choke on such large-scale systems. In order to handle the large dimensionality of the problem, some clever pre-processing has to be done. One *possible* approach[4] may be found in the report "Optimality of SVD Controllers", by Hovd, Braatz, and Skogestad (available at http://www.chembio.ntnu.no/~skoge/publications/1996/svd_long/ or in published form in [8]). Note that the process model in this project satisfies Definition 1, and look at Theorem 1 for design guidelines.

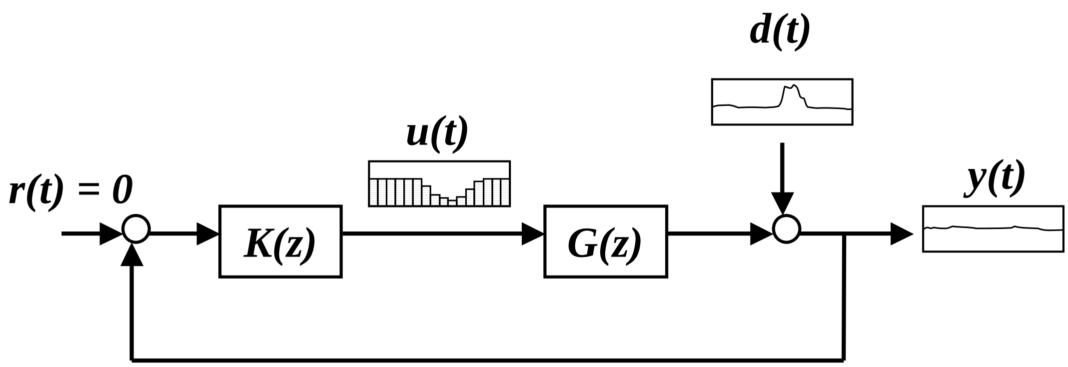

Figure 8: CD control system configuration.

Design controllers for both the newsprint and the linerboard systems described above. Matlab's Robust Control Toolbox [3] contains algorithms that will work with discrete time systems. You should be able to use the same general design procedure for each system even though the issues facing each are different. Your controller design should consider the following:

- Nominal and robust stability (NS and RS).

  Nominal stability is a must for every control system. Nominal stability can be either proved mathematically or demonstrated for a particular system. Most controller synthesis techniques in your text book will generate controllers which result in a nominally stable closed-loop. Describe how your chosen technique achieves nominal stability .

  What are the stability margins of your design? Show that your two closed-loop systems will be stable for the appropriate uncertainty set. In other words, the set Π_A in (8) for the newsprint and the set Π_B in (9) for the linerboard system.

- Nominal and robust performance (NP and RP).

  In order to test your controller design, an example benchmark disturbance has been included in each of the data files (*consistency.mat* and *linerboard.mat*). We will assume that the output disturbances in each system are described by,

$$d(t) = \begin{cases} zeros(m,1) & t < T \\ disturbance & t \geq T \end{cases} \tag{10}$$

  where $T > 0$ is a number large enough such that the initial transient effects of your simulation will not affect your results.

  Good performance is defined by a paper mill as

[4] Certainly not the only approach!

– To achieve the minimum possible variance in the steady-state ($\omega = 0$). For this exercise, you may consider the variance at time t as the vector norm $\|y(t)\|_2 = \sqrt{y(t)^T y(t)}$.

– To eliminate disturbances from $y(t)$ as quickly as possible.

– To maintain the actuator profile $u(t)$ to be smooth. In CD control, the control engineer often finds that the actuator profile has a 'picket-fence' appearance. This should be avoided if possible. Figures 9 and 10 illustrate this specification. The controller used in Figure 10 is preferred due to the fact that a significantly smoother actuator profile was able to provide almost the same performance as the pickety actuator profile shown in Figure 9.

One measure of actuator profile 'smoothness' can be obtained by measuring the size of $\|B \cdot u(t)\|_2$, where the constant $n \times n$ matrix,

$$B = \text{toeplitz}([2, -1, zeros(1, n-2)]) \tag{11}$$

which is closely related to the usual numerical approximation to the second-order derivative.

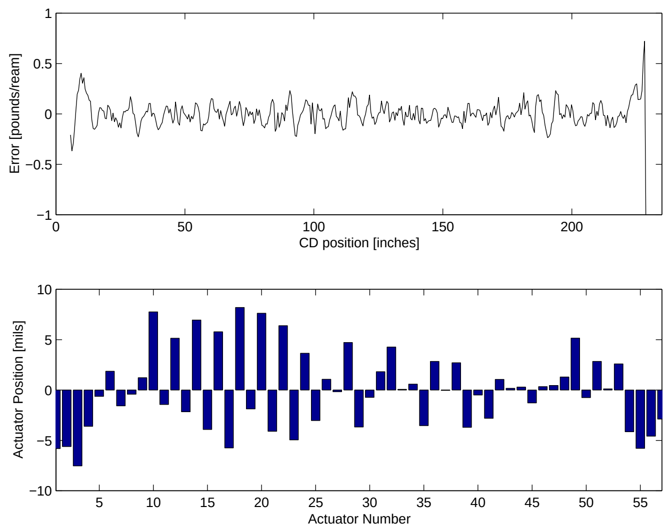

Figure 9: Example of a system with a picketing actuator profile.

Demonstrate the closed-loop performance of your systems by simulating the systems' response to the output disturbance in (10). Be sure to show performance from a representative selection of process models from Π_A in (8) for the newsprint and the set Π_B in (9) for the linerboard process.

Your controller design procedure should produce results that will satisfy the requirements listed above. However, you should not feel that you must incorporate these specifications *directly* in your synthesis strategy. For example, you may find it easier to restate these engineering requirements in a related, but not necessarily equivalent, mathematical format. These specifications are stated from the paper mill's perspective and the requirements are given in terms of the time domain and the appearance of the system. This is a natural language for humans, but many synthesis techniques work with the frequency domain and singular vector directions. Part of your job as a control engineer is learning to translate physical requirements into mathematical problems that can be solved with existing controller synthesis techniques.

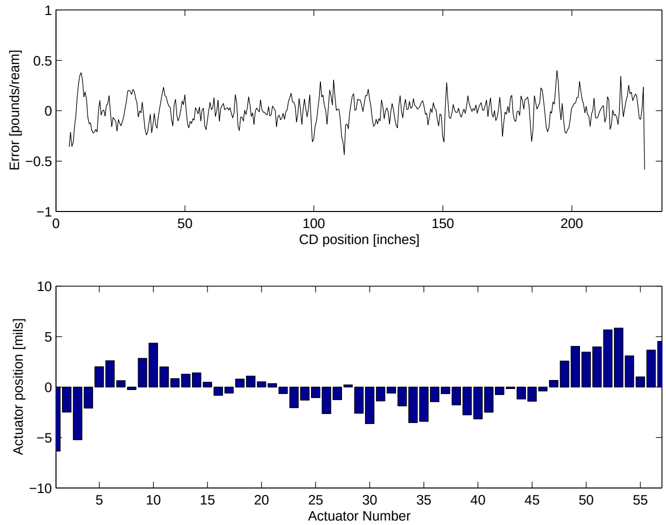

Figure 10: The actuator picketing, visible in Figure 9, has been eliminated by retuning with a more conservative controller. In comparison with Figure 9, the value of $\|u(t)\|_2$ was reduced by about 32%, while the value of $\|y(t)\|_2$ was only increased by about 3%.

4 Questions

1. The majority of control systems have "zero steady-state error" as a requirement. Is this a realistic specification for these CD control systems? Explain.

2. A recent technical paper claims that "... when there is a mapping error larger than one half of the spacing between the actuators, the control is unstable, even with a very small control gain" [10]. Is this comment valid?

3. What qualitative features characterize closed-loop instability that is caused by alignment uncertainty?

4. Suppose that a device is invented that mitigates the effect of sheet wander and has the effect of reducing the alignment uncertainty to $\pm$1cm (in other words $\delta = -1, 0, +1$ in (8)). You (a control engineer) are asked if this will allow the control system to make better paper?

5. Do you think that you could have improved closed-loop performance if you had chosen a different $M\Delta$ structure to represent Π_A? What about Π_B?

References

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There are many references listed in this bibliography. However, it is NOT meant to imply that all of these are required reading for the project!