Theory and Practice of Cross-Directional Control Systems with Industrial Applications

A proposal for a one-day pre-conference workshop at the ACC 2007 Conference, New York.

1. Course Overview

Cross-directional (CD) control systems are used in many industries that coat or form sheets of materials, such as paper making, hot and cold rolling of metals and plastic film extrusion. The first CD control systems were introduced in the paper and metal rolling industries over twenty-five years ago, but it is only recently that these control systems have been developed to the point where they are routinely fitted to new processes. Despite the fact that they are now commonplace, cross-directional controllers are complex and a high level of care and attention is required to ensure that they perform satisfactorily. This complexity does not come from the dynamic response of the process, which typically has an open loop response that is slow and stable, but instead from the high dimensions and the inherent uncertainty of the system.

This course will show how concepts from modern control can be used in the effective design and operation of CD control systems and these ideas will demonstrated through the use of interactive Matlab based simulations that can be used by individual participants.

2. Intended Audience

- Technical staff from process industries that use CD control who wish to understand the key issues in CD control. In particular, it will provide understanding that will help when selecting commercial CD control systems. It will also enable technical staff to better understand and monitor the performance of these systems.
- Staff from suppliers of CD control and sensing systems seeking an insight into the application of modern control theory to the design of their products.
- Academics, particularly those interested in the design of optimal control systems for large scale, uncertain systems, who are seeking a challenging and relevant application for their research. The course will draw on recent developments in multivariable frequency domain control design, linear and nonlinear robustness theory and Bayesian system identification and process monitoring techniques.

3. Course Outline

1. Introduction (1 hour)

1.1 Overview of CD processes and the industries where they apply (paper making, metal rolling, plastic film extrusion, coating, galvanising, converting, printing, non-wovens, multi-layer packaging, carpets and underlay, wallpaper).
1.2 Benefits of control for these processes from both a commercial and a technical point of view. This will include a discussion of the fact that CD processes tend to be used in mature industries, where small changes in productivity have big effect on profit and return on capital and where ensuring quality specifications are met is essential for protecting customer share.
1.3 Typical quality specifications and the costs of failure to achieve these specifications. The effect on throughput of downtime in production and the consequences of shorter product cycles.
1.4 Translating these challenges into the terminology of modern control:
- disturbance rejection when running in steady state,
- rapid response following grade change, splits.

1.5 Academic interest in CD control.

2. Description of processes (1 hour)

2.1 Overview of paper making, hot and cold metal rolling and plastic film extrusion, with brief description of coating and galvanising and printing, in each case focussing on:
- property being controlled,
- actuators used,
- sensors (both scanning and fixed arrays).

2.2 2-dimensional nature of disturbances that need to be controlled. Concept of both spatial and dynamic controllable bandwidths.

3. Generic model of process and introduction to CD control (2 hours, including interactive sessions)

3.1 Description of generic model of process and introduction to use of interactive simulation. Discussion of assumptions made in deriving the model together with justification
3.2 Concept of spatial modes
3.3 Series of interactive exercises covering
- Response of actuators
- Disturbance models
- Basic control
- Control of different modes
- Robustness and model uncertainty

3.4 Control challenges. Although the process is inherently open loop stable, it is challenging to control because:
- Inherent ill-conditioning of response of actuators

- Highly sensitive to uncertainties in spatial response
- The effect of constraints
- Importance of correct choice of actuators and sensors
- Multiple arrays of actuators

4. Use of Modern Control Theory in the Design of CD Controllers (1 hour)

4.1 Unconstrained design using IMC and the effect of different forms of uncertainty (gain error, error in dynamics, error in spatial shape, mapping error) on stability of control system.
4.2 Unconstrained design with anti-windup – analysis using sector bounds
4.3 Constrained design with single horizon using IQC
4.4 Long horizon MPC
4.5 Demonstration of benefits and limitations of these control approaches using interactive simulations

5. Process Identification (1 hour)

5.1 Importance of identifying the spatial response. This will focus especially on the actuator mapping.
5.2 Identification using bump tests and random perturbations in closed loop. Review of algorithms for identifying the response given the results of an identification trial and discussion of the practical aspects of identification
5.3 Using a Bayesian approach to improve statistical inference in system identification and the analysis of control system robubstness

6. Design of Actuators and Sensors (1 hour)

6.1 Importance of correct design of actuators and sensors.
6.2 Concept of spatial frequency and its use in analysis of CD control systems
6.3 Link between sampling theory, actuator spacing and spatial bandwidth of actuator array
6.4 Design of actuators and sensors to achieve a specified level of control. Illustration of concept using the interactive simulation.

8. **Performance monitoring (1 hour)**

8.1 Benefits of performance monitoring. Use interactive simulation to show that system can be stable, but not performing satisfactorily.
8.2 Statistical techniques for monitoring and diagnosing the performance of cross-directional control systems. The application of useful methods such as spectral analysis and change-point analysis.
8.3 Measuring the performance of cross-directional control systems. This will include assessing the system performance against its control objective and applying the minimum variance benchmark to cross-directional control systems in order to assess performance against optimum.
8.4 Using a nominal model of the process to monitor the performance of the control system.

4. Course Instructors

Stephen Duncan has over twenty years' experience of designing and implementing cross-directional control systems for sheet processes and he has published over 50 articles on the subject in books, scientific journals and conference proceedings. A CD control system that he designed for a plastic film process has been implemented on fourteen extrusion lines throughout the world and he has worked with many companies in this field, including ICI, 3M, Corus, DuPont Teijin Films, Innovia Films and NDC Infrared Enginnering. He is a Reader in the Department of Engineering Science at the University of Oxford, UK, where he is a member of the Control group. He is also a Fellow of St Hugh's College. Prior to joining Oxford, he was Reader in the Control Systems Centre at the University of Manchester (1993 to 1998) and a Director of Greycon Limited (a spin-out company from Imperial College, London). He has an MA in Physics from the University of Cambridge and an MSc and PhD in Control Systems from Imperial College, London. He is an Honorary Editor of the IET Proceedings Control Theory & Applications.

William Heath has been a Senior Lecturer at the Control Systems Centre in the School of Electrical and Electronic Engineering, University of Manchester since 2004. He was a Research Academic at the University of Newcastle, Australia from 1998 to 2004, following several years in industry. He has an MA in Mathematics from the University of Cambridge and an MSc and PhD from the University of Manchester (UMIST). He has a long standing interest in constrained cross-directional control for steel rolling, plastic film extrusion and papermaking applications. He designed a cross-directional controller for Infrared Engineering and has worked with many companies, including ABB.

Andrew Taylor has worked in the plastics industry for almost 20 years. At present, he is specialising in process control with one of his particular areas of expertise being the cross-directional control systems that are used to minimise thickness variation of extruded film. He is especially interested in using the analysis of data from these systems together with system identification techniques to optimise their performance. During his years in industry, he has also gained a great deal of experience in the practical implementation of process monitoring and process control systems. He has just started a part time secondment to Oxford University as a Visiting Research Fellow where he is researching cross-directional control. Prior to his current employment, Andrew was a Teaching Company Associate with the Industrial Statistics Research Unit at Newcastle University. He graduated with BSc in Statistics at Aberdeen University and gained a DPhil at Oxford University in cross-directional control. He has been a Fellow of the Royal Statistical Society since 1988.