MVC and MPC

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Congratulations to a Stellar Career!

- Points of tangency

- IFAC Teddington 1964
- IFAC Prague 1967 First Identification Symposium
- Generalized predictive control Automatica 1987
- A memorable semester as Douglas Holder Visiting Fellow Oxford in 1988
- Control is much more than algorithm design; diagnostics, fault detection and reconfiguration are also of prime significance.
Introduction

Minimum Variance Control

- Inspired by practice
- Åström 1966 (IBM J R&D 1967)
- Model structure MISO
- Explicit disturbance modeling
- Minimize variance
- Identification
- Self-tuning
- Harris index

Model Predictive Control

- Inspired by practice
- Richalet 1976 (Automatica 1978)
- Cutler DMC (ACC 1980)
- Model structure MIMO-FIR
- Reference trajectory
- Captures saturation
- Widely used in industry

What can we learn?

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MVC and MPC
Outline

- Introduction
- The IBM-Billerud Project
- Modeling
- Minimum Variance Control
- Adaptation
- Reflections
The Scene of 1960

- Servomechanism theory 1945
- IFAC 1956 (50 year jubilee in 2006)
- Widespread education and industrial use of control
- The First IFAC World Congress
  Moscow 1960
- Exciting new ideas
  - Dynamic Programming Bellman 1957
  - Maximum Principle Pontryagin 1961
  - Kalman Filtering ASME 1960
- Exciting new development
  - The space race (Sputnik 1957)
  - Computer Control Port Arthur 1959
- IBM and Nordic Laboratory 1961
The Role of Computing

- Vannevar Bush 1927: *Engineering can proceed no faster than the mathematical analysis on which it is based. Formal mathematics is frequently inadequate for numerous problems, a mechanical solution offers the most promise.*
- Herman Goldstine 1962: *When things change by two orders of magnitude it is revolution not evolution.*
- Gordon Moore 1965: *The number of transistors per square inch on integrated circuits has doubled approximately every 12 months.*
- Moore+Goldstine: *A revolution every 10 year!*
- Unfortunately software does keep up with hardware
- Roughly 10 years between MVC and MPC
The Billerud-IBM Project

Background
- IBM and Computer Control
- Billerud and Tryggve Bergek

Goals
- Billerud: Exploit computer control to improve quality and profit!
- IBM: Gain experience in computer control, recover prestige and find a suitable computer architecture!

Schedule
- Start April 1963
- Computer Installed December 1964
- System identification and on-line control March 1965
- Full operation September 1966
- 40 many-ears effort in about 3 years
Goals and Tasks

Goals
- What can be achieved by computer control?
- Find an architecture of a process control computer!

Philosophy
- Cram as much as possible into the system!

Tasks
- Production Planning
- Production Supervision
- Process Control
- Quality Control
- Reporting

Later 1969
- Millwide control
Computer Resources

- IBM 1720 (special version of 1620 decimal architecture)
- Core Memory 40k words (decimal digits)
- Disk 2 M decimal digits
- 80 Analog Inputs
- 22 Pulse Counts
- 100 Digital Inputs
- 45 Analog Outputs (Pulse width)
- 14 Digital Outputs
- Fastest sampling rate 3.6 s
- One hardware interrupt (special engineering)
- Home brew operating system
The Billerud Plant

- 660,000 ADt/year
- Three fiber lines
- Six paper machines

Containerboard
Sack
Kraft
Market pulp
Summary

Industrial

- A successful installation
- Computer architecture for process control
  IBM 1800, IBM 360

Methodology

- Method for identification of stochastic models
- Basic theory, consistency, efficiency, persistent excitation
- Minimum variance control

What we missed

- Project was well documented in IBM reports and a few papers but we should have written a book
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Process Modeling

- Process understanding and modifications (mixing tanks)
- Physical modeling
- Logging difficulties
- Drastic change in attitude when computer was installed
- Good support from management Kai Kinberg:
  “This is a show-case project! Don’t hesitate to do something new if you believe that you can pull it off and finish it on time.”
- The beginning of system identification
- Wasted a lot of time on historical data
- Big struggle to do real plant experiments
- Identifications requires a great range of skills
Basis Weight and Moisture Control

- Two important loops
- Triangular coupling MISO works
Modeling for Control

- Modeling by frequency response key for success of classical control
- Stochastic control theory is a natural formulation of industrial regulation problems
- State space models for process dynamics and disturbances
- Physical models may give dynamics
- Process data necessary to model disturbances
- Can we find something similar to frequency response for state space systems?
Typical Fluctuations

First measurement of fluctuations in basis weight 1963

Availability of sensor crucial!
A lot of effort to obtain this curve!
Stochastic Control Theory

Kalman filtering, quadratic control, separation theorem

Process model

\[ dx = Ax \, dt + Bu \, dt + dv \]
\[ dy = Cx \, dt + de \]

Controller

\[ d\hat{x} = A\hat{x} + Bu + K(dy - C\hat{x} \, dt) \]
\[ u = L(x_m - \hat{x}) + u_{ff} \]

A natural approach for regulation of industrial processes.

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Model Structures

Process model

\[ dx = Axdt + Budt + dv \]
\[ dy = Cxdt + de \]

Much redundancy \( z = Tx + \) noise model. The innovation representation reduces redundancy of stochastics and filter gains appear explicitly in the model

\[ dx = Axdt + Budt + Kd\epsilon \]
\[ = (A − KC)xdt + Budt + Kdy \]
\[ dy = Cxdt + d\epsilon \]

Canonical form for MISO system removes remaining redundancy, discretization gives (C filter dynamics)

\[ A(q^{-1})y(t) = B(q^{-1})u(t) + C(q^{-1})e(t) \]
Modeling from Data (Identification)

The Likelihood function (Bayes rule)

\[ p(\mathcal{Y}_t, \theta) = p(y(t)|\mathcal{Y}_{t-1}, \theta) = \cdots = -\frac{1}{2} \sum_{1}^{N} \frac{\epsilon^2(t)}{\sigma^2} - \frac{N}{2} \log 2\pi \sigma^2 \]

\[ \theta = (a_1, \ldots, a_n, b_1, \ldots, b_n, c_1, \ldots, c_n, \epsilon(1), \ldots) \]

\[ Ay(t) = Bu(t) + Ce(t) \quad C\epsilon(t) = Ay(t) - Bu(t) \]

\[ \epsilon = \text{one step ahead prediction error} \]

Efficient computations

\[ \frac{\partial J}{\partial a_k} = \sum_{1}^{N} \epsilon(t) \frac{\partial \epsilon(t)}{\partial a_k} \quad C \frac{\partial \epsilon(t)}{\partial a_k} = q_k y(t) \]

- Estimate has nice properties Åström and Bohlin 1965
- Good match identification and control. Prediction error is minimized in both cases! Cleaned up by Lennart Ljung ...
Practical Issues

- Sampling period
- To perturb or not to perturb
- Open or closed loop experiments
- Model validation
- 20 min for two-pass compilation of Fortran program!
- Control design
- Skills and experiences
Results
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Control

- Conventional PI(D) at lower level
- Simple digital control for non-critical loops
- Limited computational capacities
- Time delay dynamics stochastic fluctuations dominating
- Mild coupling basis weight and moisture control
- Minimum variance control and moving average control
- Robustness performance trade-offs
Minimum Variance (Moving Average Control)

Process model

\[ Ay(t) = Bu(t) + Ce(t) \]

Factor \( B = B^+ B^- \), solve (minimum \( G \)-degree solution)

\[ AF + B^- G = C \]

\[ Cy = AFy + B^- Gy = F(Bu + Ce) + B^- Gy = CFe + B^-(B^+ Fu + Gy) \]

Control law and output are given by

\[ B^+ Fu(t) = -Gy(t), \quad y(t) = Fe(t) \]

where \( \text{deg } F \geq \text{pole excess of } B/A \)

True minimum variance control \( V = E \frac{1}{T} \int_0^T y^2(t) dt \)
Properties of Minimum Variance Control

- The output is a moving average
  
  \[ y = Fe, \quad \deg F \leq \deg A - \deg B^+. \]

  Easy to validate!

- Interpretation for \( B^- = 1 \) (all process zeros canceled), \( y \) is a moving average of degree \( n_{pz} = \deg A - \deg B \). It is equal to the error in predicting the output \( n_{pz} \) step ahead.

- Closed loop characteristic polynomial is
  
  \[ B^+ C z^{\deg A - \deg B^+} = B^+ C z^{\deg A - \deg B^+ + \deg B^-}. \]

- The sampling period an important design variable!

- Sampled zeros depend on sampling period. For a stable system all zeros are stable for sufficiently long sampling periods.
Performance \( (B^- = 1) \) and Sampling Period

Plot prediction error as a function of prediction horizon \( T_p \)

\[ \sigma^2_{pe} \]

\( T_d \) is the time delay and \( T_s \) is the sampling period. Decreasing \( T_s \) reduces the variance but decreases the response time.
Strong similarity between all controller for systems with time delays, minimum variance, moving average and Smith predictor.

*It is dangerous to be greedy!*

Rule of thumb: no more than 1-4 samples per dead time motivated by simulation.
Robustness Analysis

Consider a system with time delay $T_d$ design for a closed loop time constant $T_{cl}$. The main system functions are:

$$G_t(s) = \frac{e^{-sT_d}}{1 + sT_{cl}}$$

$$G_s(s) = 1 - G_{cl}(s) = 1 - \frac{e^{-sT_d}}{1 + sT_{cl}}$$

$$G_\ell(s) = \frac{e^{-sT_d}}{1 + sT_{cl} - e^{-sT_d}}$$

Sensitivity and complementary sensitivity functions are always less than 2! So things look good!

BUT Look at the delay margins!
Nyquist Plots for Smith Predictors $T_{cl} = 1$

- $T_d = 1$
- $T_d = 2$
- $T_d = 4$
- $T_d = 8$
Another Robustness Result

A simple digital controller for systems with monotone step response (design based on the model $y(k + 1) = bu(k)$)

$$u_k = k(y_{sp} - y_k) + u_{k-1}, \quad k < \frac{2}{g(\infty)}$$

Stable if $g(T_s) > \frac{g(\infty)}{2}$  
Summary

- Regulation can be done effectively by minimum variance control
- Easy to validate
- Sampling period is the design variable!
- Robustness depends critically on the sampling period
- The Harris Index and related criteria
- OK to assess but why not adapt?
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Drawbacks with System Identification

- Experiment planning requires prior knowledge
- Process perturbations required
- Time consuming
- Requires competence
- Adaptation is an alternative
The Self-tuning Regulator

- Process model: \( Ay(t) = Bu(t - k) + B_{ff}u_{ff}(t) + Ce(t) \)
- Select sampling period and time delay \( k \), rules for stable systems
- Estimate parameters in the model

\[
y(t + k) = Sy(t) + Ru(t) + R_{ff}u_{ff}(t)
\]

- If estimate converge
  \[
  r_y(\tau) = 0, \tau = k, k + 1, \ldots k + \deg(S)
  
  r_{yu}(\tau) = 0, \tau = k, k + 1, \ldots k + \deg(R)
  
  \text{If degrees sufficiently large } r_y(\tau) = 0, \forall \tau \geq k
  
  - Convergence conditions

KJÅ+BW Automatica 9(1973),185-199
Convergence Analysis

Analysis of Recursive Stochastic Algorithms

Lennart Ljung, Member, IEEE

IEEE Trans AC-22 (1977) 551–575

Markov processes and differential equations

\[ dx = f(x)dt + g(x)dw, \]
\[ \frac{\partial p}{\partial t} = -\frac{\partial p}{\partial x} \left( \frac{\partial f \theta}{\partial x} \right) + \frac{1}{2} \frac{\partial^2}{\partial x^2} g^2 f = 0 \]

Lennarts idea

\[ \theta_{t+1} = \theta_t + \gamma_t \varphi e, \]
\[ \frac{d\theta}{d\tau} = f(\theta) = E\varphi e \]

Convergence of recursive algorithms and STR (Ay=Bu+Ce)

Jan Holst: ODE locally stable if \( \text{Re} C(z_k) > 0 \) for \( B(z_k) = 0 \)
Paper Machine Control

![Graphs showing moisture and control signal over time with annotations for start of self-tuning regulator and set point of refiner energy increased or decreased.](image-url)
Industrial Applications

- A number of applications in special areas
- Paper machine control
- Ship steering
- Rolling mills
- Semiconductor manufacturing
- Tuning of feedforward very successful
- The Novatune
- Process diagnostics Harris and similar indices
Tuning and Adaptation

**Categories**
- Automatic Tuning
- Gain Scheduling
- Adaptive feedback
- Adaptive feedfoward

**Products**
- Tuning tools
- PID controllers
- Tool boxes
- Special purpose systems built into instruments

Process dynamics

- Varying parameters
  - Use a controller with varying parameters
  - Unpredictable variations
    - Use an adaptive controller
- Constant parameters
  - Use a controller with constant parameters
  - Predictable variations
    - Use gain scheduling

Åström Hägglund Advanced PID Control, 2004
What happens when relay feedback is applied to a system with dynamics? Think about a thermostat?
The Excitation Signal

- Relay feedback automatically generates an excitation signal with good frequency content!
- The transient is also useful
Temperature Control of Distillation Column

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MVC and MPC
Commercial Auto-Tuners

- Easy to use
  - One-button tuning
  - Semi-automatic generation of gain schedules
  - Adaptation of feedback and feedforward gains
- Robust
- Many versions
  - Stand alone
  - DCS systems
- Large numbers
- Excellent industrial experience

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Properties of Relay Auto-tuning

- Safe for stable systems
- Close to industrial practice
  
  Compare manual Ziegler-Nichols tuning
  Easy to explain
- Little prior information. Relay amplitude
- One-button tuning
- Automatic generation of test signal
  
  Automatically injects much energy at $\omega_{180}$ without for knowing $\omega_{180}$ apriori
- Good for pre-tuning of adaptive algorithms
- Good industrial experience for more than 25 years. Basic patents are running out.
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Interaction with Industry

- Contact with real problems is very healthy for research in engineering
- Both MVC and MPC emerged in this way
- Applied industrial projects can inspire research, provided that they have enlightened management
- New problems may appear
- Challenges with publications; importance of good Editors
- Necessary to look deeper and to fill in the gaps, even if it takes a lot of effort and a lot of time - a long range view is necessary to get real insight
- Useful for a project to exchange people between academia and industry
- The Oxford model, the SupAero model, the Lund model
The Knowledge Gap

- Richalet Automatica 1963: MPC requires technical staff with training in:
  - modeling, identification, digital control,...
- The Novatune experience
  - Projects 73-74
  - Bengtsson Cold rolling 79
  - ASEA Innovation 81
  - 30 persons 50M
  - Transfer to ASEA Master
- Relay auto-tuning Hägglund kjå 1981
  - One button tuning
- Can relay auto-tuning be useful for MPC modeling?