Model Predictive Control for Energy Efficient Control
- Direct Commercial Value of Research

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Outline

• Model Predictive Control

• DRYControl – Energy Efficient Control of Spray Dryers
  A Case Study at GEA Process Engineering A/S

• The Industrial PhD Program – A way to develop energy-management and energy efficient control software

• IEA – Energy Efficient Control
Computer Controlled Systems

Computer

\[ y_k \rightarrow u_k \]

Communication Network

\[ y_k \rightarrow u_k \]

Sampler & A-D

\[ y(t) \rightarrow u(t) \]

D-A & Hold

Process
Communication: Read & Write

Display Application

Trend Application

MPC Application

Software Driver

Software Driver

Software Driver

Software Driver

DTU Compute, Technical University of Denmark
Read & Write using OPC

Display Application
OPC Client

Trend Application
OPC Client

MPC Application
OPC Client

OPC Server Software Driver

OPC Server Software Driver

OPC Server Software Driver

OPC Server Software Driver
Connection of MPC App to Plant

Industrial IT is accessing, monitoring and controlling physical plant hardware
MPC – Basic Idea

Estimation and regulation problem

Moving horizon implementation
Role of MPC in the Operational Hierarchy

- **Plant-Wide Optimization**
  - Unit 1 Local Optimizer
  - Unit 2 Local Optimizer
  - High / Low Select Logic
  - Model Predictive Control (MPC)

**Global steady state optimization** (every day)

**Local steady state optimization** (every hour)

- **Make fine adjustments for operating conditions of local units**

**Dynamic constraint control** (every minute)

- **Take each local unit to the optimal condition.**
- **Reject Disturbances.**

**Basic dynamic control** (every second)
Structure of Optimizer & MPC

- Optimizer
  - Steady State Economic Optimization
  - Detector

- MPC
  - Dynamic Regulator
  - Estimator

- Disturbances
  - Process
  - Sensors

Measurements
Technical Advantages of MPC

- **Explicit process models allow control of difficult dynamics**
  - Dead-time (time delay)
  - Inverse response
  - Interactions (multivariate)
  - Nonlinearity

- **Optimization of future plant behavior handles**
  - Feedforward from measured or estimated disturbances
  - Feedforward from setpoint changes and desired future trajectory
  - Feedback

- **Input and output constraints are handled by the controller**
- **Infrequent and irregular laboratory measurements**
Economic Benefit of Process Control

No APC

APC reduces variation

Reduced variation allows operation closer to the limit

Safety Margin

Target

Limit
Economic Benefit of Process Control
Economic Benefit of Process Control

Economic value added by feedback control

Squeeze & Shift

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Rapid Product Change

The graph illustrates the behavior of a process under rapid product change. The top graph shows the controlled variable over time, with a sharp change at around time 100. The bottom graph depicts the manipulated variable, which responds to the change in the controlled variable. The diagrams are marked with dashed lines to indicate the desired and actual trajectories.
Economic Benefits of Process Control

Disturbance Rejection

- APC reduces variation
- Reduced variation allows operation closer to the limit

Reference Tracking

- Controlled Variable
- Manipulated Variable

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Example Applications

• Distillation Plants
• An Artificial Pancreas for People with Diabetes
• Production Optimization of Oil Reservoirs
• Cement Processes
• Commercial Refrigeration
• Smart Energy Systems
• Spray Drying Processes
• U-Loop Reactor for Production of SCP
• NOx reduction from diesel engines
## Typical Improvements – Danish Distillers Project

<table>
<thead>
<tr>
<th>Type of improvement</th>
<th>Background</th>
<th>Improvement</th>
</tr>
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</table>
| Quality             | 3 grades of spirit:  
a) KA/KO  
b) Korn (better)  
c) Premium (best) | Possible to produce best grade at all times if desired.  
Higher flexibility. |
| Capacity            | Before: 18000 L 100% / d  
After: up to 19800 L 100% / d | 9-10% improvement |
5,0 kg steam / L 100% spirit.  
After (3rd quarter 2001):  
4,5-4,7 kg steam / L 100% spirit | Estimated 6-10% improvement (not finalized running in modifications yet) |
Economic Model Predictive Control for a Spray Drying Plant

Industrial PhD stud., Lars Norbert Petersen
Introduction

• The Multi-Stage Dryer (MSD™) is the prime process for the production of food powders.

• Why milk powder? Long shelf life and reduced transportation costs with great nutritional value.

• Continuous process. 4.4 million l/day of milk, means that approx. 260,000 cows must be milked each day.

• The process is highly energy consuming.

• Product quality varies
The Multi-Stage Dryer

- **Outputs**
  - Exhaust air temperature + humidity
  - Powder temperature in SFB/VFBs
  - Powder residual moisture

- **Inputs**
  - Feed flow
  - Inlet air temperature

- **Disturbances**
  - Ambient air humidity
  - Feed changes
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Physical setup

- Interface and features
  - Bad measurement indication?
  - Measurement delay indication?
  - New measurement indication?
  - PROFIBUS, 4-20mA etc.
Simulation Model vs Experimental Values

- $T_{SD}$
- $T_{SFB}$

**Graphs:**
- Temperature ($T$ [°C])
- Concentration ($Y$ [g/kg])
- Solids content ($X$ [% t.m.])

**Axes:**
- Time [hours]

**Legends:**
- Measured
- Simulated
Performance

Residual Moisture %:

Exhaust Air Temperature:

Disturbances:
MPC vs PID Control

Graphs showing the performance comparison between PID and MPC control systems for production rate, efficiency, and cost over time.

- **Production Rate [kg/hr]**
  - PID: Red line
  - MPC: Blue line

- **Efficiency [%]**
  - PID: Red line
  - MPC: Blue line

- **Cost [$/hr]**
  - PID: Red line
  - MPC: Blue line
Industrial PhD Project

- Commercial product available after 1.5 years of PhD study
  **DRYControl**
- First two systems already installed
- More systems ordered
- **Improvement of operational economics (including energy)**
  5% guaranteed. In practice 5-10%.
**Industrial PhD Program**

- Joint project by a company and a university
- 3 year program
- The project is conducted by an industrial PhD student
- Approximately 50% of the cost is paid by the Ministry for Research and Innovation
- The PhD student must do research and development activities

- Transfer of knowledge from universities to companies
- Transfer of relevant research topics from companies to universities

- Result in highly qualified persons that understand commercial aspects related to research

- In 2014, the International Energy Agency have established activities related to Energy Efficient Control

- The outcome will be a number of workshops and white papers about best practices for energy efficient control within a number of different industries

- These white papers will be presented to the energy departments of the governments that are member of IEA – and will most likely be implemented in the legislations to improve energy efficiency in the process industries

- Denmark is leading the activities
  - You have the chance to participate such that your technology is among the best-practice technologies
The planning tool suggests how to dispatch the production and reserves (every 5 minutes)
The Faroe Island Power System
• Thermal Storage
  – Heating of floors etc
  – Heating of water accumulation tanks
  – Refrigeration Systems

• Power / Heat Producers
  – Wind Turbines
  – Photovoltaic Solar Modules
  – Solar Panels
  – CHP Plants
  – Fuel Cells
Connected Energy Systems
Electricity & Heating / Cooling

**Inputs**
- electricity
- natural gas
- district heat
- wood chips

**Outputs (loads)**
- electricity
- heating
- cooling

**Energy Hub**