SUCCESSFUL METHODOLOGY TO SELECT ADVANCED CONTROL APPROACH
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- Founder and President of TOP Control Inc., now a member of BBA inc. (>600 p.)
- Registered Professional Engineer, university lecturer and author of several publications and books on instrumentation and control
- For over 38 years, he has been solving unusual process control problems in several fields in more than 16 countries
- Graduated from Laval University, Québec, Canada, with a Bachelor of Science, Electrical Engineering (Process and Automation)
- Member of the following organizations:
  - ISA, Fellow (International Society for Automation)
  - IEEE (Institute of Electrical and Electronic Engineers)
  - AIChE (American Institute of Chemical Engineers)
  - PEO (Professional Engineers of Ontario)
  - OIQ (“Ordre des ingénieurs du Québec”)
Agenda

• **Introduction**
• Need for Advanced Control
• Approaches
• Selection
• Comparison
• Conclusion
IT-OT Model

Optimization

- B.I.
- ERP / Maint. Syst.
- MES / Historian
- SCADA / HMI
- PLC / DCS / RTUs
- Instruments

Advanced Control

IT (Transactionnel)

OT (Temps réel)

(ref. Gartner http://www.gartner.com/it-glossary/operational-technology-ot/)
Process Control ➔ Control Loops

<table>
<thead>
<tr>
<th>Plant</th>
<th>Loops</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentrator</td>
<td>200-500</td>
<td>Physical</td>
</tr>
<tr>
<td>Metal, Metallurgy</td>
<td>200-1,000</td>
<td></td>
</tr>
<tr>
<td>Pulp and Paper Mill</td>
<td>500-1,500</td>
<td></td>
</tr>
<tr>
<td>Thermal Plant</td>
<td>50-500</td>
<td>Chemical</td>
</tr>
<tr>
<td>Hydro Plant</td>
<td>10-100</td>
<td>Chemical</td>
</tr>
<tr>
<td>Chemical</td>
<td>100-300</td>
<td>Chemical</td>
</tr>
<tr>
<td>Refinery</td>
<td>1,000-5,000</td>
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</tr>
</tbody>
</table>

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Control Loops Mean Opportunities!

Operations: SP, mode

Variability

Normal mode?

Tuning

In service?

In control?

Non-linearities

Backlash

Saturation

Stiction

Disturbance

Process model

Control design

Fouling

Oscillations

FIC-101

FT-101

FT-101

Interactions

Noise

Process design

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Process Control in North America

- 20% control loops have the wrong design
- 30% valves have problems
- 15% equipment were incorrectly installed
- 30% controllers have nonsensical tuning parameters
- 85% tuning parameters are inappropriate
- 30% controllers are in the wrong mode (manual)
- **Only 25% of control loops improve control performance**
Optimization

- Optimize operation of existing assets
- Identify what you need to get more
- Plan the next steps

Advanced Control

- If basic controls are insufficient
- If basic controls have been optimized
- If performance is below expectation
- Two choices for APC:
  - Model the process and calculate controls to reach objectives
    - Model predictive control (MPC)
  - Model the best operator
    - Fuzzy logic control (FLC)
Optimization

- Maximize your assets
The Impacts of Optimization

Reduce variability through optimization

- Maintenance saving$
- Saving$
- SAVINGS $$$
- SAVINGS $$$
- Economie$

Before optimization

After optimization

Limit(Client)

SP
PV
CO

400 600 800 1000 1200 1400 1600

400 600 800 1000 1200 1400 1600

0 5 10 15 20 25 30

0 5 10 15 20 25 30

Moisture (%)

Time (s)

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Need for Advanced Process Control

• Use APC to:
  – Improve performance
  – Stabilize production
  – Handle constraints
  – Handle interactions
  – Protect equipment
  – Manage grade changes

• Approaches
  – Advanced Regulatory Control (PID control +++)
  – Model Predictive Control
  – Fuzzy Logic Control
  – Neural Network
Before evaluating APC

- The following questions must be answered:
  - Are the performances adequate?
  - Have the loops been optimized?
    - All loops should be optimized
    - All equipment should be verified
    - All control strategies should be reviewed
  - Do the control systems handle disturbances?
  - Do the control loops interact?
  - Does an operator perform better than the control system?
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Model-Based or Rules-Based Systems

- Model-based control (usually the first choice)
  - advanced regulatory control
  - model predictive control
- Rules-based control
  - fuzzy logic control
Advanced Regulatory Control

- Cascade
- Feedforward
- Ratio
- Override, Constraint
- Mid-Range
- PID +++
- …
Pump Box Level

PY Unit
Pump Box Level BPY-1
Cascaded to Level FICxYC504
Under Constraint on min Pump Speed PSY-5,

Feedforward Logic on:
Pump Start-Up PSY-5
Valve Closing NVxYC51B
Material Handling

Bin Level by Feeder Modulation
AG Control

Ore Bin

%Solid

Pressure

Power

Stator T

Feed

Calc

DIK C2

FIC C3

FIC C3

WIT C1

PV

SP

Eau

AG Mill

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pH Control
Model Predictive Control

- MPC
  - for processes with strong coupling among variables, competing optimization goals and limited process constraints
  - predicts future behaviour
    → based on dynamic models of the process
    → obtained through system identification
MPC principle

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Process problems

- 9 furnaces producing up to 50,000 ft\(^3\)/min (~85,000 m\(^3\)/h) of CO
  - ~equivalent volume of 15 houses per minute or interior volume
- 22 consumers burning this CO (combustible)
  - Random consumption, random generation, start and stop all the time
  - Total consumption > or < than supply
  - When CO is not available, Natural gas (CH\(_4\))
  - 3 pressure levels (different headers), ~1PSI, 3 PSI, 15 PSI
  - In 13 different systems, in 5 business units, using different programming languages

- Often, some consumers burn natural gas while CO is flared

- Solution
  - MPC (Model Predictive Control) controller predicting generation and consumption
  - Priority table to decide when allowing or not consumption
  - New communication system to collect all data (~1,000 tags)
  - 4,500 hours for BBA personnel (3 offices, 15 people)
Model Predictive Control to Manage CO

Buffer ~ 1 minute
Reaction time, 2-3 minutes
Predictive Control

Based on gasholder level

Modulates CO/natural gas ratio for rotary kilns

Based on predictions for fuel consumption and generation

Authorizes and de-authorizes

4,500 hours (BBA), 15 people, 3 offices
Information exchange and programming across 23 systems
Savings of $X millions per year
Fuzzy Logic Controller

• Decisions are made based on analog inputs representing a value ranging from 0 (false) to 1 (true)

• The logic deals with partially true and partially false values

• Fuzzy logic control is used when an experienced operator has better control over a process than a PID or MPC

• Fuzzy logic emulates an experienced operator and reacts to process behaviour and variable trends
Fuzzy vs. PID

The density is too high. I’ll increase water flow.

\[ \text{OP} = K_p \left( e + \frac{1}{T_i} \int_0^t e \, dt + T_d \frac{de}{dt} \right) + \text{Bias} \]
Membership function defines if element is or is not a member of the set, either

- “in” degree of membership = 1.0
- “out” degree membership = 0.0

Membership function defines:

- The degree of membership (or fulfillment) of any element in the fuzzy set
- Partial membership is allowed
- 22.5 °C is partly (20%) ‘cold’ and partly (80%) ‘warm’
Controller Structure (PLC function blocks)

**Inputs**
- $X_n$ and $dX_n/dt$
- Numerical → Membership function
- 3 to 7
- Adjustable weights

**Rules**
- Logic (Inputs, Outputs)
- Adjustable weights

**Outputs**
- Mix of all fired rules
- Membership function → Numerical
- 3 to 7
- Adjustable weights

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Fuzzy Logic Control for SAG

Measurements (controlled)
- Density
- Power
- Load (bearings pressure)
- Recirculation

Disturbances
- Sandvik gap
- Granulometry
- Hardness

Manipulated
- Speed
- Feed (tonnage)
- Water flow
SAG

- 24 ft x 10.5 ft
- 3300 HP motor
- Variable Speed (69-84%)
- Grinding Media: 5” balls
- Steel Liners + Lifters
Partnership: Xstrata + BBA

- Fuzzy controller in place since 2007
- Process changes, operation is different
- Adding speed control
- Maximize and stabilize tonnage
- Ensure consistency in the actions taken
- Ensure autonomy
  - Maintenance, Modifications
  - Targets, New Rules…
Controller Structure

**Fuzzification**

**Decisions**

(rules)

If T is … AND … THEN (423)

**Defuzzification**

**Inputs**

**Outputs**

**Shapes**

**Weights**

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<table>
<thead>
<tr>
<th>Rule</th>
<th>Pressure</th>
<th>Pressure Rate</th>
<th>Power</th>
<th>Power Rate</th>
<th>Tonnage</th>
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<td>...</td>
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</table>
Controller Structure

### Shapes

- Load (5)
- dLoad/dt (5)
- OreSize (3)
- dOreSize/dt (3)
- Recirculation (5)
- dRecirculation/dt (5)
- Power (5)
- dPower/dt (5)
- Density (5)
- dDensity/dt (5)

### Decisions (rules)

If T is …

### Defuzzification

- Tonnage (7)
- Water flow (5)
- Rotation speed (5)

### Rule

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### Weights

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Controller Design

Objectives

- To reduce power consumption per ton of ore
- Increase throughput
- Protect linings and stabilize quality and operation

Determining Rules

- Design of experiments (DOE) to determine how the SAG mill should be operated
- These tests were conducted in different conditions
- All tests were conducted during the summer of 2011
- Which resulted in hundreds of rules
- Rules were then chosen to reach the selected goals and to push the feed rate to its maximum
Controller Design

Membership Functions
- Shapes based on DOE
- Number based on expected ranges and rules

Rules
- More than 500 (MIMO)
- Structured + State identification

Programming
- PLC fuzzy functions
- Workarounds for bugs and optimization
- Support tools for maintenance
Commissioning and Optimization

• Advisory mode 3 days
• 4 days, FLC was used during the day shift
  – optimization
• 8th day, FLC was used continuously 24/24
• 10th day, production record
• Every week
  – metallurgists validate the rules and make slight adjustments
• Training
  – operators, metallurgists, maintenance technicians and engineers
• Maintenance
  – Plant personnel maintain the system, modify the controller, add rules and optimize the controller
Tools

Statisticals to support metallurgists

- Historian
- Rules used (% time, strength, etc.)
- Statistical data on rules and inputs
- Key performance indices:
  - Tons/d, kW/ton, average error, etc.

Performance Monitoring Software

- KPI
- Utilization
- Performance
Results

Utilization > 95%

Evolution

Production

Specific Energy

Month

175
170
165
160
155
150
15
14.5
14
13.5
13
January 2011
February
March
April
May
June
July
August
September
October
November
December
January 2012
February
March

Commissioning and Optimization

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Results

![Graph showing SAG feed rate (t/hr) over time with labels "Before" and "After". The graph illustrates a comparison of feed rate data from September 2011 to February 2012.](image-url)
Results

• This project was carried out over six months

• The team consisted of:
  – Consultant personnel, metallurgists from the plant and operators

• Operators have quickly gained confidence and performances have been improved:
  – Utilization > 95%
  – Energy per ton has been reduced by 8%
  – Tonnage per day has been increased by 14%
  – A production record was achieved during the first week, then 5x
  – The savings generated by the fuzzy logic controller covered the project’s cost in less than three months
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**SISO and MIMO**

- **SISO, Single Input, Single Output**
  - Each loop is "alone"
  - One model per loop

- **MIMO, Multiple Inputs, Multiple Outputs**
  - Models for input/output +
  - Models for interaction +
  - Models for disturbances
Multi Loop Process Control, MIMO

Controller

Process

Disturbances

SP

CO

PV

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Modeling

Small SP excitation (Closed Loop)
Automated Standardized Tests
Normal Operation
Multi Loop
No need to stabilize the process
Automated

Results
- Models matrix
- Quality of models
- Error bound
Models are identified or calculated

- **SISO**
  - 1 PV, 1 CO
    - Good process model → PID controller
    - Non linear process model or models → PID controller + gain scheduling (or PID)

- **MIMO**
  - n PVs, mCOs
    - Good process models, weak interactions → PID controllers
    - Good process models, interactions → PID controllers, tuned at different speeds
    - Good process models, strong interactions → PID controllers + decouplers
      → MPC
No process models identified nor calculated

**SISO**
- 1 PV, 1 CO
  - No process model
  - Best operator can be "modeled"
- PID controller, relaxed tuning parameters
- PID controller + logic + functions
- Fuzzy logic controller

**MIMO**
- n PVs, mCOs
  - No process model
  - Best operator can be "modeled"
  - Best operator cannot be "modeled"
  - Data available
  - No data
  - PID controllers, relaxed tuning parameters + logic + enhanced functions
  - Fuzzy logic controller
  - Neural network
  - Re-design!
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PID vs. APC

Is Advanced Regulatory Control Sufficient?

Yes

PID
Feedforward
Decoupling
Adaptive Gains
Characterizers

No

Can Process be Modeled?

Yes

MPC

No

Can Best Operator Control?

Yes

Fuzzy Logic

No

Neural Network
## Comparison

<table>
<thead>
<tr>
<th>Approach</th>
<th>Model</th>
<th>Rules</th>
<th>Historical</th>
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<tbody>
<tr>
<td>Control</td>
<td>ARC</td>
<td>MPC</td>
<td>FLC</td>
</tr>
<tr>
<td>Description</td>
<td>PID, Control strategies</td>
<td>Process is modelled</td>
<td>Operator is modelled</td>
</tr>
<tr>
<td>Usage</td>
<td>Few variables</td>
<td>Good models</td>
<td>Best operator</td>
</tr>
<tr>
<td>Development</td>
<td>Simple</td>
<td>Moderate</td>
<td>Complex</td>
</tr>
<tr>
<td>Commissioning</td>
<td>Simple</td>
<td>Moderate</td>
<td>Long but easy</td>
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<tr>
<td>Optimization</td>
<td>Simple</td>
<td>Part of design</td>
<td>Cumbersome</td>
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<tr>
<td>Process changes</td>
<td>Simple</td>
<td>Re-model</td>
<td>Review rules and membership functions</td>
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<tr>
<td>Maintenance</td>
<td>Simple</td>
<td>Needs expert</td>
<td>Easy</td>
</tr>
<tr>
<td>Cost</td>
<td>Low</td>
<td>High</td>
<td>Moderate</td>
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</table>
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Conclusions

Steps:

• Base layer optimization:
  → PID, soft sensors, control strategies

• Performance analysis

• Modeling

• Decision tree

• Selection of best approach

• Controller design
Thank you!

Questions?

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