From process control to business control:

*How the philosophy and methods of process control can be applied to businesses: key performance indicators, logistics, markets, management and other?*

Trial Lecture
Deeptanshu Dwivedi
18th Jan, Trondheim
Scope of the lecture

• Introduction to Process Control
• Feedback & Feed forward Control
• Optimal Control Theory
• Stochastic Control Theory
• Model Predictive/ receding horizon control
• Self-Optimizing Control
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Process Control

• **Control** in Process Industries
  – control process variables (like T, P) when manufacturing a product

• Objectives of Process Control
  – Ensure safety
  – Reduce variability
  – Increase profits

• Process Industries
  – the chemical industry
  – oil and gas
  – the food and beverage industry
  – the pharmaceutical industry
  – water treatment industry
  – etc
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Feedback Control

- **Simple**: tight control with only a very crude model.
- **Robustness**: can adapt to new conditions.
- **Stabilization**: fundamentally change the dynamics of a system
Feedback Control: Example

<table>
<thead>
<tr>
<th></th>
<th>Process Control</th>
</tr>
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<tbody>
<tr>
<td><strong>System</strong></td>
<td>Reactor</td>
</tr>
<tr>
<td></td>
<td>(to maintain temperature)</td>
</tr>
<tr>
<td><strong>Controlled Variable</strong></td>
<td>Temperature</td>
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<tr>
<td><strong>Sensor</strong></td>
<td>Temperature transmitter</td>
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<td>Feed Flow rate</td>
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![Diagram of a Temperature Loop](image-url)
## Feedback Control: Analogy

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<tr>
<td><strong>System</strong></td>
<td>Room Heater, Reactor (to maintain temperature)</td>
<td>Academic Institute* (maintain effective education)</td>
</tr>
<tr>
<td><strong>Controlled Variable</strong></td>
<td>Temperature</td>
<td>Grades, Employment, Publications, Awards</td>
</tr>
<tr>
<td><strong>Sensor</strong></td>
<td>Temperature transmitter</td>
<td>Surveys</td>
</tr>
<tr>
<td><strong>Manipulated variable</strong></td>
<td>Valve position</td>
<td>Changes in the curriculum, Faculty-Student ratio</td>
</tr>
<tr>
<td><strong>Disturbance</strong></td>
<td>Feed Flow rate</td>
<td>Change in population, demographics etc.</td>
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*Arkun, Y. (2009)
Feedback Control: Analogy..
Feed forward Control

Take proactive corrective action by measuring disturbance
### Feed Forward Control: Analogy

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<td>Feed forward</td>
<td>Model</td>
<td>Model/ Forecast</td>
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Especially in business/management problems, there is a large time delay, so feed forward may be a good policy

- Use proactive policies using forecasts
Feedback-Feed forward Combination

• Difficulty to account for every possible load disturbance in a feed forward system
  - Uncertainty causes instability

• Use feedback/ forecast both to make manage the educational institute
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Optimal Control Theory

- Deals with optimization of dynamic systems from one state to another
- Optimal control problem*

Maximize
\[ J = \int_0^T F(x,u,t) \, dt + S[x(T), T] \]

subject to,
\[ \dot{x} = f(x,u,t), x(0) = x_0 \]

Aim is to find, \( u^* \) & \( x^* \)
\( u^* \), optimal control
\( x^* \), optimal trajectory

- Problem may be solved numerically

*Sethi & Thompson (2009)
Optimal Control Theory..

\[ u^* \]

\[ x^* \]
Optimal Control: Optimum cash

Optimum cash balance: firms need cash on hand

• If too much cash
  – loss in terms opportunity cost (securities have higher rate of interest)

• If too little cash
  – will need to sell securities (=loss due to brokerage fees)

• Find tradeoff between cash and securities
## Optimal Control: Optimum cash...

<table>
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<tr>
<th>Objective*</th>
<th>Maximize $J = [x(T) + y(T)]$</th>
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<tr>
<td>Constraints (state equations)</td>
<td>$\dot{x} = r_1 x - d + u - \alpha</td>
</tr>
<tr>
<td>Constraints (control equations)</td>
<td>$\dot{y} = r_2 y - u$, $y(0) = y_0$</td>
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where,
- $x$ = the cash balance in NOK
- $y$ = security balance in NOK
- $d$ = instantaneous rate of demand for cash
- $u$ = rate of sale of securities
- $r_1$ = interest rate earned on the cash balance
- $r_2$ = interest rate earned on the security balance
- $\alpha$ = the broker's commission in dollars

\*Sethi & Thompson (2009)
Optimal Control: A Production-Inventory System

• Inventory: Production-inventory are need to manage fluctuations in customer demand for the product

• Pros
  – Immediately available for demand
  – Inventory stock may be used in reaction to market prices

• Cons
  – Cost of storage
  – Opportunity cost of firm’s money tied in unused inventory
## Optimal Control: A Production-Inventory System

| Objective* | maximize
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<tr>
<td></td>
<td>[ J = \int_{0}^{T} e^{-\rho t}[h(I - \hat{I})^2 + c(P - \hat{P})^2] dt ]</td>
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| Constraint (state equation) | \[ \dot{I} = P(t) - S(t), I(0) = I_0 \] where, \]
|                           | \[ I = \text{inventory level} \]
|                           | \[ P = \text{production rate} \]
|                           | \[ S = \text{sales rate at time} \]
|                           | \[ \hat{I} = \text{inventory goal} \]
|                           | \[ \hat{P} = \text{production goal} \]
|                           | \[ h = \text{inventory holding cost coefficient} \]
|                           | \[ c = \text{production cost coefficient} \]
|                           | \[ \rho = \text{nonnegative discount rate} \]

*Sethi & Thompson (2009)*
Optimal Control: Nerlove-Arrow Advertising Model

- Advertising is an investment to make **Goodwill**

- **Goodwill, }G(t)\):
  \[ \dot{G} = u - \delta \cdot G \]
  
  - \( u \) is advertising effort, say in NOK
  - Depreciates with time at a rate \( \delta \) (as consumers “drift” to other brands)
Optimal Control: Nerlove-Arrow Advertising Model

| Objective* | maximize 
\[
J = \int_{0}^{T} e^{-\rho t} [R(p, G, Z) - u] dt
\]
where, 
\(R = \text{revenue}\)
\(p = \text{price}\)
\(G = \text{Goodwill}\)
\(Z = \text{exogenous variables like, consumer income, population size etc.}\)
\(u = \text{advertising effort}\) |
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Stochastic Control

• A stochastic control problem:
  – What is the optimal magnitude of a choice variable at each time in a dynamical system under uncertainty

• Stochastic process:
  \[ dX(t) = b(X(t)) \, dt + \sigma(X(t)) \, dB(t) \]
  where,
  \( b = \) drift term
  \( \sigma = \) diffusion term
  \( \{B(t)\} = \) standard Brownian motion

• \( X(t) \) may be exogenous factors
## Stochastic Optimal Control: A Production-Inventory System

| Objective* | maximize $J = E\left[\int_0^T e^{-\rho t} \{h(I - \hat{I})^2 + c(P - \hat{P})^2\} dt\right]$  
$E[I]$ is the expectation of $I$ |
|---|---|
| Constraint (state equation) | $\dot{I} = (P(t) - S(t))dt + \sigma d B(t), I(0) = I_0$  
where,  
$I = \text{inventory level}$  
$P = \text{production rate}$  
$S = \text{sales rate at time}$  
$\hat{I} = \text{inventory goal}$  
$\hat{P} = \text{production goal}$  
$h = \text{inventory holding cost coefficient}$  
$c = \text{production cost coefficient}$  
$\rho = \text{nonnegative discount rate}$  
$\sigma = \text{white noise (sales return / inventory spoilage)}$ |

*Morimoto, Hiroaki (2010)*
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Model Predictive Control

• Open-loop optimal solution is not robust
• Must be coupled with on-line state / model parameter update
• Requires on-line solution for each Open-loop optimal !!
  – Analytical solution possible only in a few cases (LQ control)
• Very successful in process industries like refinery & petrochemicals
Model Predictive Control..

1. At time $k$, solve the open-loop optimal control problem on-line with $x_0 = x(k)$
2. Apply the optimal input moves $u(k) = u_0$
3. Obtain new measurements, update the state and solve the at time $k+1$ with $x_0 = x(k+1)$
4. Go to step 1
Model Predictive Control: Stochastic MPC

- Examples: Polymerization reactor
- Supply chains
- Dynamic hedging
- Sustainable development
- MATLAB Financial toolbox 😊
Stochastic MPC: Portfolio Optimization

• Portfolio is any collection of financial assets
  – Stocks (unit of ownership in a company)
  – Bonds (instrument of indebtedness of the bond issuer to the holders)
  – Cash

• Portfolio optimization
  – changing the set of financial instruments held to meet various criteria
    most notably, Financial risk

• Financial Risk:
  – Asset-backed risk, credit risk, foreign investment risk, liquidity risk, market risk etc
Stochastic MPC: Portfolio Optimization..

• asset price dynamics by stochastic differential equations
  – instantaneous expected returns and instantaneous volatility of the asset
    price dynamics are functions of the factors

• maximizing a utility function

• Solutions by Hamilton–Jacobi–Bellman equation
Stochastic MPC: Portfolio Optimization

- Asset based model*: 
  - Linear Gaussian factor model

  Rate of Return
  
  \[ r(t + 1) = \mu(t, x(t)) + \varepsilon^r(t) \]

  \( \varepsilon^r = \) white noise of risky asset
  \( \mu = \) the expected rate of return
  \( x = \text{exogenous factors} \)

  Prices of risky assets
  
  \[ P_i(t + 1) = P_i(t)(1 + r_i(t)) \]

  \( r_i(t) = \) exogenous factors

  \[ x(t + 1) = \Theta(t,x(t)) + \Psi(t,x(t))\varepsilon^x(t) \]

Stochastic MPC: Portfolio Optimization..

- Portfolio optimization problem

\[ J = \max_{u(t),q(t)} E\left[ \sum_{t=0}^{T} U_1(q(t)) + U_2(W(T)) \right] \]

\[ U \text{ : utility functions capturing risk} \]
\[ W \text{ : Wealth} \]
\[ u \text{ : distribution of assets} \]
\[ q \text{ : consumption} \]

if consumer is only interested in utility at the end of time

\[ J = \max E\{U_2(W(T))\} \]
Stochastic MPC: Portfolio Optimization..

Receding Horizon Control

• Based on the information at time $t$, measure (for example stock prices $P_i(t)$, exogenous factors $x(t)$).
• Compute the open-loop optimization problem
• Apply only the first control decision, i.e., $u(t)$, of the sequence $u(t), u(t+1), \ldots, u(T-1)$ and we move one time step ahead.
• Go to step 1

Other example:
Railways (Schutter & Boom, 2001), air traffic management (Zhang et al, 2012), logistics (Daganzo & Erera, 1999)
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Self-optimizing Control

- Hierarchal Control*
  - Regulatory layer
    - Control unstable/integrating modes
    - CVs which would otherwise drift
  - Supervisory layer
    - Steady state local optimizer gives set points
    - Otherwise, “self-optimizing”
      - variables when kept constant ensure acceptable operation without needing optimizing layer
        - insensitive to disturbances
        - easy to measure & control
        - sensitive to manipulated variables
        - *Significant amount of theory has been developed in this group*
  - Self-optimizing variables for production planning & scheduling??

*Skogestad (2001)
Self-optimizing Control: for production planning

- What to Control at planning/scheduling layer

- In production planning, SOVs may be translated to KPIs*
  - For an objective like, Customer Delivery performance, good KPIs
    - On-time shipment %
    - average lateness of orders
    - customer query time
    - customer order lead time
    - frequency of delivery
  - For an objective like, Internal Delivery performance, good KPIs
    - production schedule attainment
    - number of order amendments
    - schedule changes

- The optimal values may be set by benchmarking/best business practices**

Acknowledgements

I would like to thank for the inputs received from:

- Prof Sigurd Skogestad (NTNU)
- Prof Heinz Preisig (NTNU)
- Prof Tore-Haug Warberg (NTNU)
- Dr Ivar Halvorsen (SINTEF)
- Dr Knut Wiig Mathisen (Advanced Process Control coordinator, Yara International ASA)
- Mr Esmaeil Jahanshahi (NTNU)
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Conclusions

• Process Control principles are/ may be used for businesses and management
  – Qualitatively &/Or Quantitatively

• Process Control theory may provide a systematic framework to make business decisions