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

NTNU – Trondheim
Norwegian University of
Science and Technology

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

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

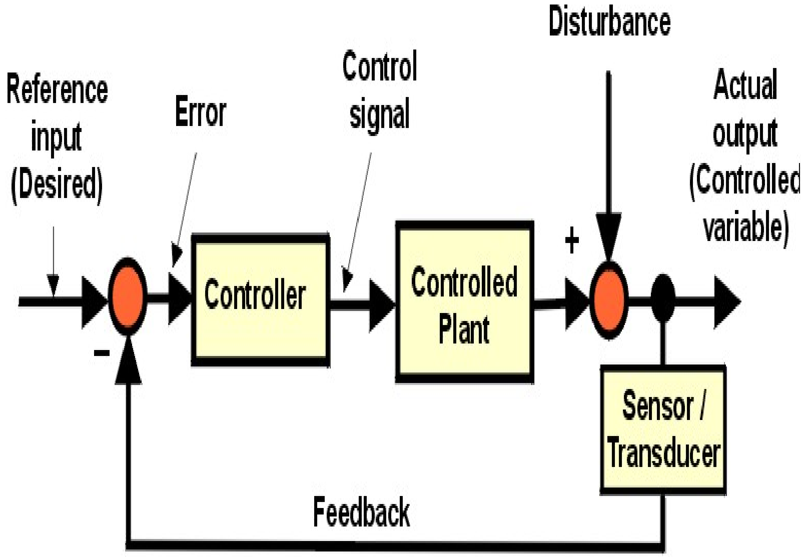
Process Control

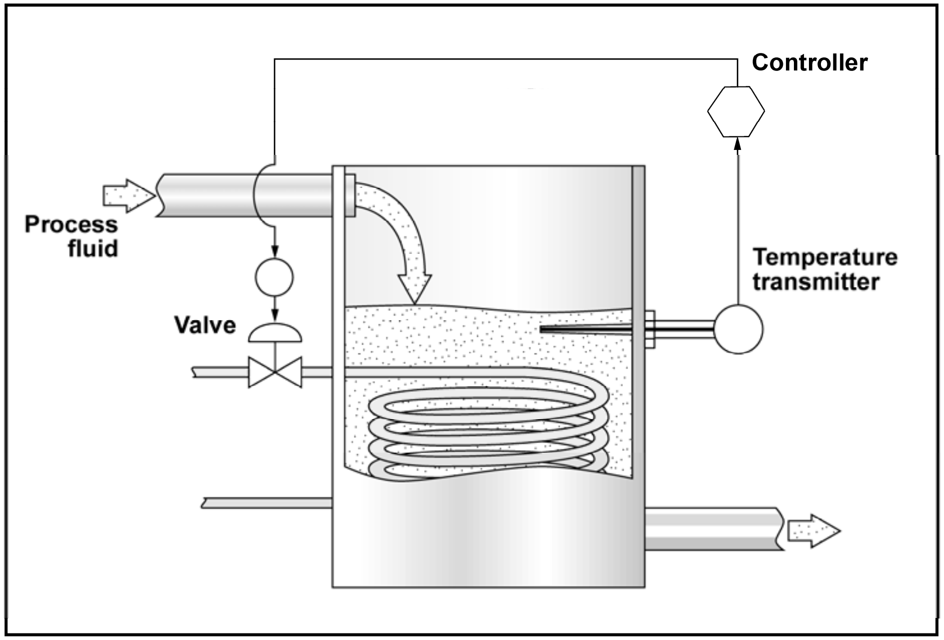
- *Control* in Process Industries
  - –control process variables (like T, P) when manufacturing a product
- Objectives of Process Control
  - –Ensure safety
  - –Reduce variability
  - –Increase profits
- Process Industries
  - –the chemical industry
  - –oil and gas
  - –the food and beverage industry
  - –the pharmaceutical industry
  - –water treatment industry
  - –etc

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

Feedback Control



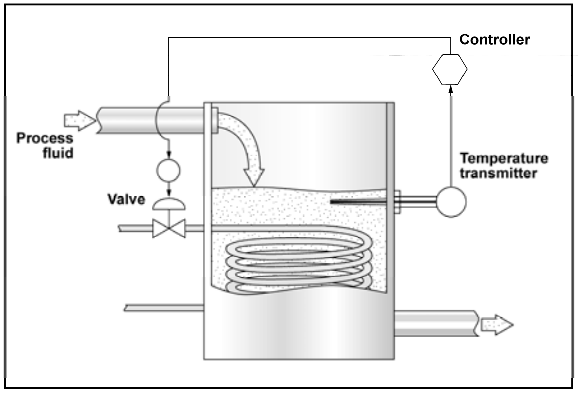


A Temperature Loop

- **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

	Process Control
System	Reactor (to maintain temperature)
Controlled Variable	Temperature
Sensor	Temperature transmitter
Manipulated variable	Valve position
Disturbance	Feed Flow rate



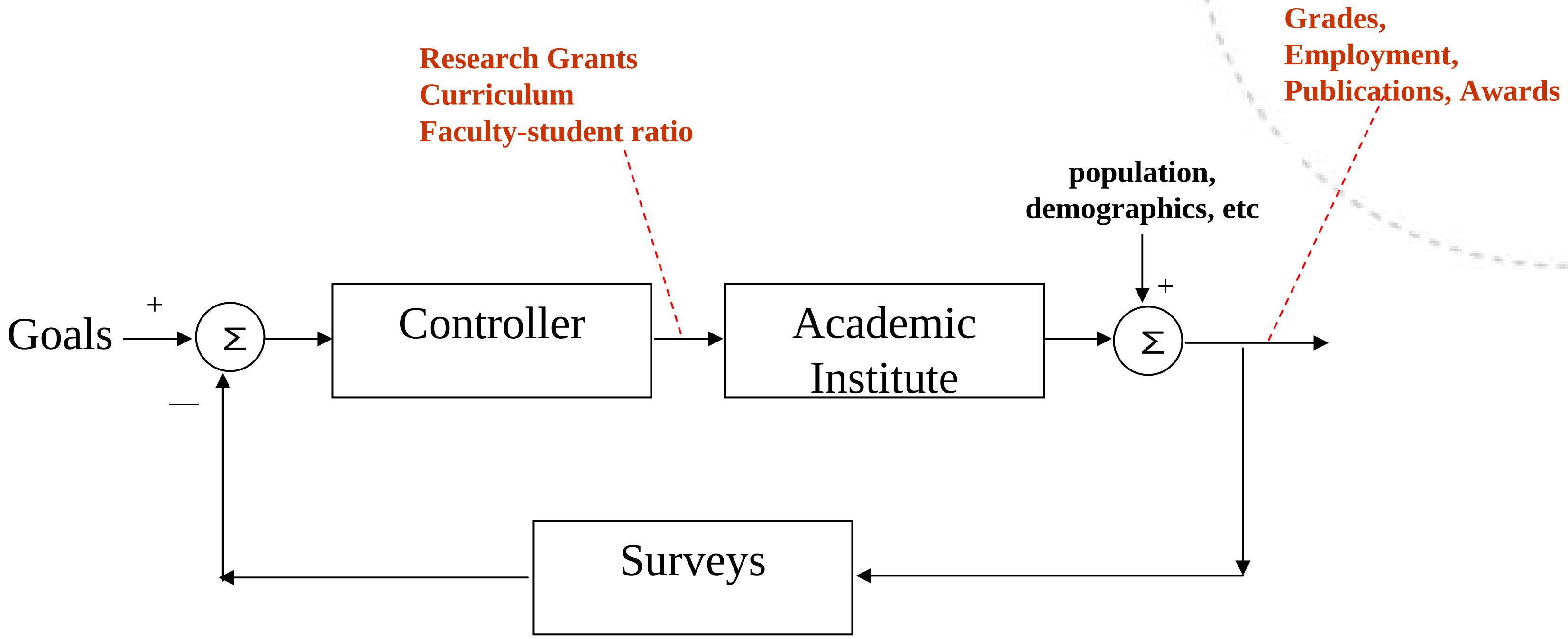
A Temperature Loop

NTNU – Trondheim
Norwegian University of
Science and Technology

Feedback Control: Analogy

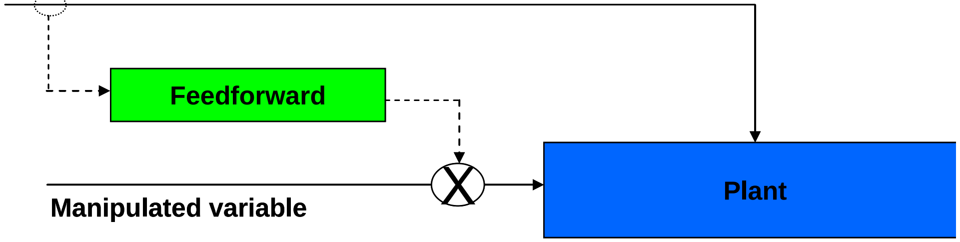
	Process Control	**Business/ Management** *Arkun, Y. (2009)
System	Room Heater, Reactor (to maintain temperature)	Academic Institute* **(maintain effective education)**
Controlled Variable	Temperature	Grades, Employment, Publications, Awards
Sensor	Temperature transmitter	Surveys
Manipulated variable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

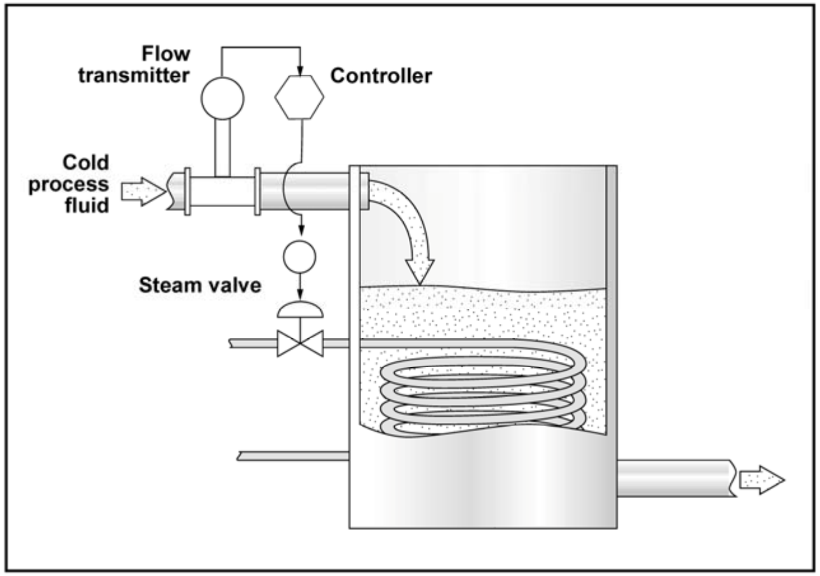
Feedback Control: Analogy..



NTNU – Trondheim
Norwegian University of
Science and Technology

Feed forward Control





Feedforward Control

Take proactive corrective action by measuring disturbance

Feed Forward Control: Analogy

	Process Control	**Business/ Management**
System	Room Heater, Reactor **(to maintain temperature)**	Academic Institute **(maintain effective education)**
Disturbance	Feed Flow rate	Change in population, demographics etc.
Feed forward	Model	Model/ Forecast

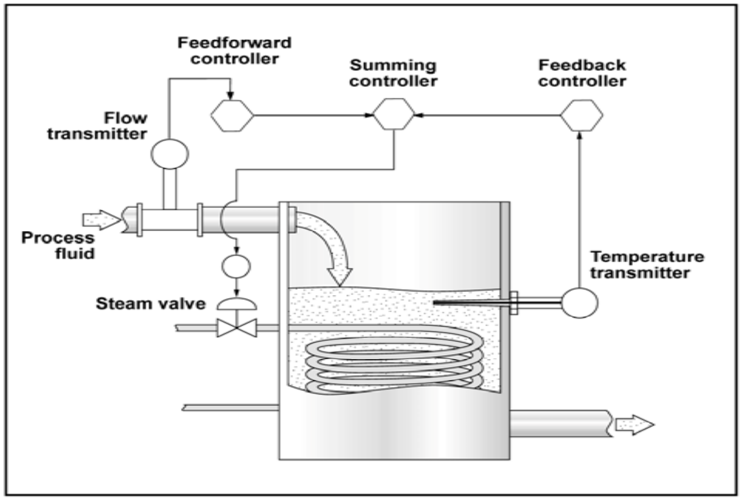
Especially in business/management problems, there is a large time delay, so feed forward may be a good policy

- 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



Feedforward Plus Feedback Control System

NTNU – Trondheim
Norwegian University of
Science and Technology

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

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^*

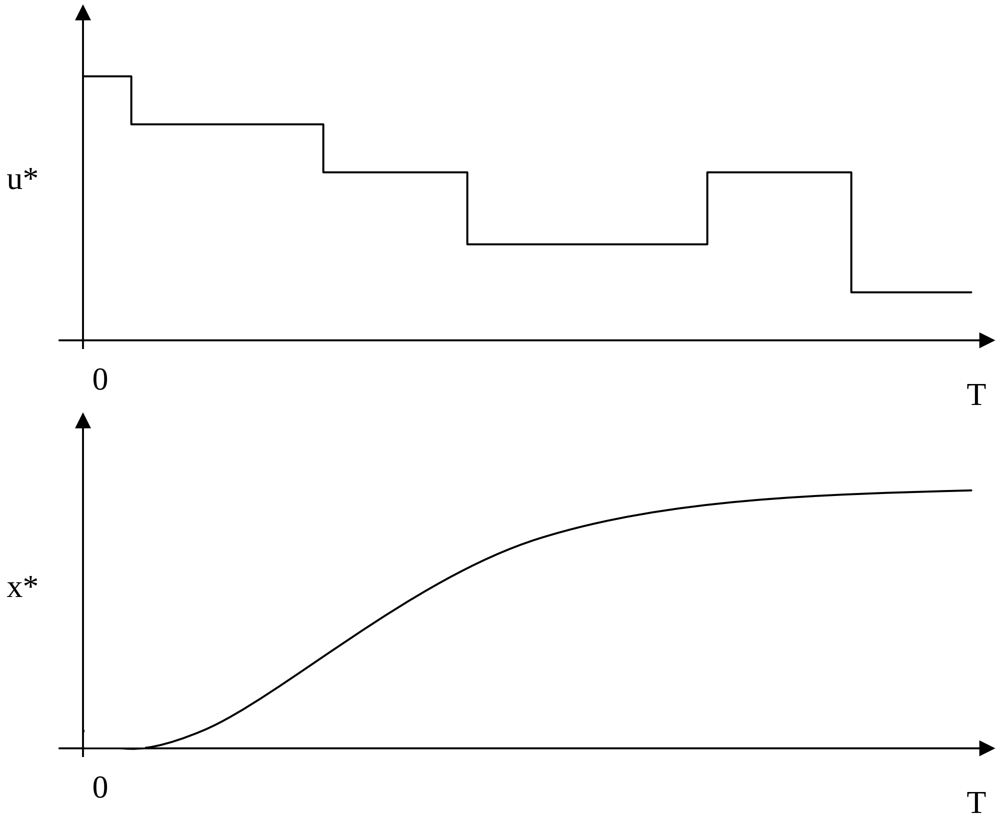
u^*, optimal control

x^*, optimal trajectory

- Problem may be solved numerically

***Sethi & Thompson (2009)**

Optimal Control Theory..



NTNU – Trondheim
Norwegian University of
Science and Technology

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..

Objective*	Maximize $J=[x(T)+y(T)]$
Constraints (state equations)	$\dot{x}=r_1x-d+u-\alpha\|u\|, x(0)=x_0$ $\dot{y}=r_2y-u,\ y(0)=y_0$
Constraints (control equations) *Sethi & Thompson (2009)	$-U_2\le u(T)\le U_1$ 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

Optimal Control: A Production-Inventory System..

- Inventory: Production-inventory are need to manage fluctuations in costumer 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 $J = \int_0^T e^{-\rho t}[h(I-\widehat{I})^2 + c(P-\widehat{P})^2]dt$
Constraint (state equation) *Sethi & Thompson (2009)	$\dot{I} = P(t) - S(t), I(0) = I_0$ where, $I =$ inventory level $P =$ production rate $S =$ sales rate at time $\widehat{I} =$ inventory goal $\widehat{P} =$ production goal $h =$ inventory holding cost coefficient $c =$ production cost coefficient $\rho =$ nonnegative discount rate

Optimal Control: Nerlove-Arrow Advertising Model

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

- ***Goodwill***, *G(t)*

$$\dot{G} = u - \delta \bullet G$$

  - *u* is advertizing effort, say in NOK
  - Depreciates with time at a rate δ (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, $R =$ revenue $p =$ price $G =$ Goodwill $Z =$ exogenous variables like, consumer income, population size etc. $u =$ advertizing effort
Constraint (state equation)	$\dot{G} = u - \delta \bullet G, G(0) = G_0$

*Sethi & Thompson (2009)

NTNU – Trondheim
Norwegian University of Science and Technology

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

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:

$$dX(t) = b(X(t))\,dt + \sigma(X(t))\,dB(t)$$

$$where,$$

$$b = \text{drift term}$$

$$\sigma = \text{diffusion term}$$

$$\{B(t)\} = \text{standard Brownian motion}$$

- *X(t)* may be exogenous factors

Stochastic Optimal Control: :A Production-Inventory System..

Objective*	maximize $J = E[\int_0^T e^{-\rho t}\{h(I-\widehat{I})^2 + c(P-\widehat{P})^2\}dt]$ $E[I]$ is the expectation of I
Constraint (state equation) *Morimoto, Hiroaki (2010)	$\dot{I} = (P(t)-S(t))dt + \sigma d\,B(t), I(0) = I_0$ where, $I =$ inventory level $P =$ production rate $S =$ sales rate at time $\widehat{I} =$ inventory goal $\widehat{P} =$ production goal $h =$ inventory holding cost coefficient $c =$ production cost coefficient $\rho =$ nonnegative discount rate $dB/dt = \mathit{white\ noise}\,(\mathit{sales\ return}/\mathit{inventory\ spoilage})$

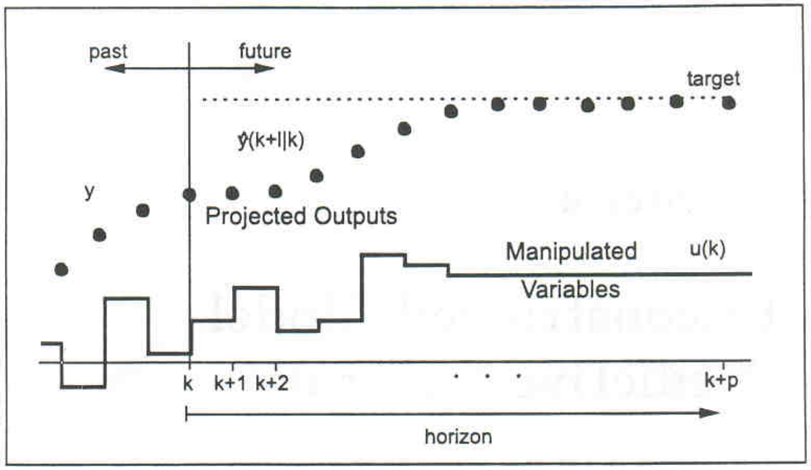
Scope of the lecture

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

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*) = *u0***
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

$$r(t+1) = \mu(t, x(t)) + \varepsilon^r(t)$$

ε^r = white noise of risky asset

μ = the expected rate of return

$x = exogenous\ \ factors$

Prices of risky assets

$$P_i(t+1) = P_i(t)(1 + r_i(t))$$

exogenous factors

$$x(t+1) = \Theta(\mathrm{t,x(t)}) + \Psi(\mathrm{t,x(t)})\varepsilon^{\mathrm{x}}(\mathrm{t})$$

Geering, et. al (2006), Primbs (2007)

Stochastic MPC: Portfolio Optimization..

- Portfolio optimization problem

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

U :utility functions capturing risk

W:Wealth

u : distribution of assets

q :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:

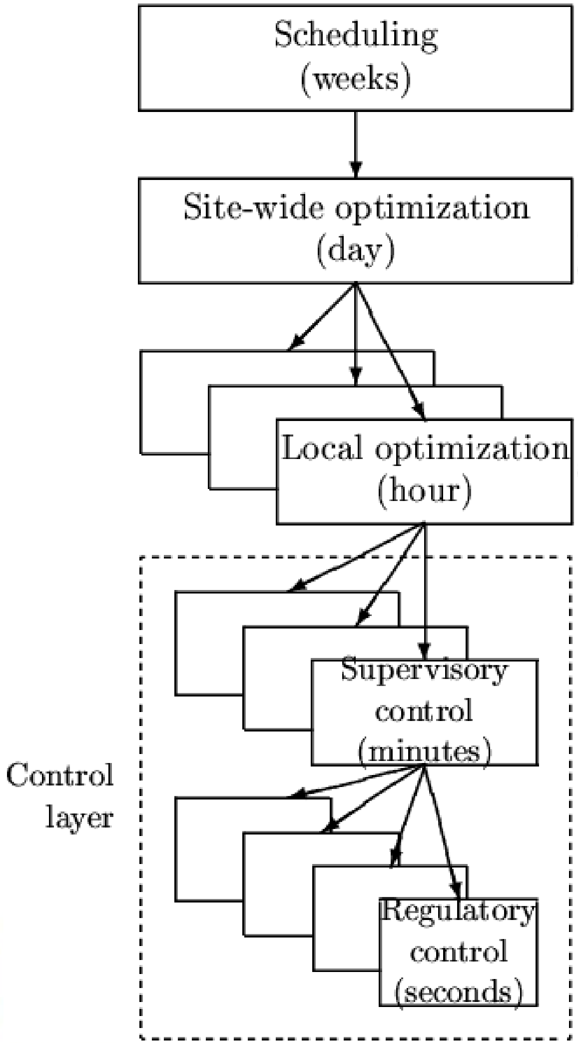
Railways (Schutter & Boom, 2001), air traffic management (Zhang et al, 2012), logistics (Daganzo & Erera, 1999)

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

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**

***Konsta & Plomaritou (2012), ** S. Skogestad (2004)**

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)

References

- Arkun, Y., “Systems Thinking and Process Control Viewpoint for Academic Administration: Toward a Learning and Continuously Improving System”, CACHE News, Summer 2009.
- Suresh P Sethi, Gerald L. Thompson, Optimal Control Theory: Applications to Management Science and Economics, Second Edition, Springer, 2000,
- Morimoto, Hiroaki, Stochastic control and mathematical modeling : applications in economics / Hiroaki Morimoto, Cambridge : Cambridge University Press, 2010
- Florian Herzog†, Simon Keel†, Gabriel Dondi, Lorenz M. Schumann, and Hans P. Geering, Model Predictive Control for Portfolio Selection, Proceedings of the 2006 American Control Conference, Minneapolis, Minnesota, USA, June 14-16, 2006
- James Primbs, Portfolio Optimization Applications of Stochastic Receding Horizon Control, Proceedings of the 2007 American Control Conference Marriott Marquis Hotel at Times Square New York City, USA, July 11-13, 2007
- Zhang et al.: A Hierarchical Flight Planning Framework for Air Traffic Management, Proceedings of the IEEE | Vol. 100, No. 1, January 2012
- Carlos F. Daganzo, Alan L. Erera, On Planning and Design of Logistics Systems for Uncertain Environments, in Distribution Logistics, vol 480 of Lecture Notes in Economics and Mathematical Systems, 1999
- B. De Schutter and T. van den Boom, Model predictive control for railway networks, International Conference on Advanced Intelligent Mechatronics Proceedings 6-12 July 2001 Como, Italy
- S. Skogestad ``Plantwide control: the search for the self-optimizing control structure'', J. Proc. Control, 10, 487-507 (2000).
- Katerina Konsta & Evi Plomaritou, Key Performance Indicators (KPIs) and Shipping Companies Performance Evaluation: The Case of Greek Tanker Shipping Companies, International Journal of Business and Management Vol. 7, No. 10; May 2012
- S Skogestad, Near-optimal operation by self-optimizing control: from process control to marathon running and business systems, Computers and Chemical Engineering 29 (2004) 127–137

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