Multivariable Process Control
– Predictive Control

1.1 Introduction

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Introduction to Predictive Control

Why predictive control?
- Multivariable systems
- Nonlinear and “difficult” systems
- Importance of constraints
- Optimal operation
- Flexible performance specification
- Disturbance rejection

The receding horizon principle

History of predictive control
Success Of Predictive Control

- What other control techniques are out there?
  - PID – by far the most successful!
  - LQR/LQG
  - $H_\infty$ control
  - Fuzzy logic and neural networks
  - Too many to list here…

- Predictive control is
  - the *only* advanced control methodology to have had any *significant* impact in industry
Multivariable Systems

- Many systems have multiple inputs and multiple outputs
- A single input can have an effect on multiple system states
- Predictive control easily copes with multivariable systems
Difficult Systems

- Unstable systems
  - Poles in right half plane
  - Without reliable control, could end up with a disaster!

- Non-minimum phase systems
  - Zeros in right half plane
  - Output responds in opposite direction to step input

- Systems with time delay
  - Output takes long time to respond to input

- Predictive control handles difficult systems in a transparent fashion

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Nonlinear Systems

- Differential equations are often nonlinear (4F3)
  - Aeroplane dynamics
  - Chemical reactions
- Saturation on variables
  - Ailerons and rudders
  - Valves
- Hysteresis and deadzones
  - Relays
  - Valves
- Predictive controllers can be designed for nonlinear systems

\[
\dot{x} = \sin(x) + xu^2
\]

\[
\dot{x} = Ax + B\text{sat}(u)
\]
Constraints Are Important

- In applications, constraints nearly always arise:
  - Physical constraints, e.g. actuator limits
  - Performance constraints, e.g. overshoot
  - Safety, e.g. temperature below critical

- Most control methods address constraints \textit{a posteriori}, e.g.
  - Anti-windup
  - Clever tricks
  - Trial and error

- Predictive control addresses constraints \textit{a priori} and allows constraints to come “out of the closet”
Optimal Operation

- Why does industry need control?
  - To make things work or work “better”
- Why does industry want things to work?
  - To make money!
- Optimal operation is often on or close to some constraints
- The goal of most controllers are:
  - Reduce variability of controlled variable (CV), and
  - Move system closer to optimal operating point
Operating Close To Constraints

- **Classical linear control**
  - High variability of CV
  - Constraint violated
  - Average far from optimal

- **Predictive control**
  - Lower variability of CV
  - Constraint satisfied
  - Average closer to optimal

Constraint (and optimal point of operation)

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Flexible Performance Specification

- Unplanned scenarios can occur, e.g.
  - A plant unit taken out for upgrading
  - Different grade of raw material
- Faults can occur, e.g.
  - Valve or aileron getting stuck
- Priorities change, e.g.
  - Avoid obstacle, rather than minimise fuel cost
- Often no time/money for off-line controller redesign
- Predictive control allows flexible performance specification and on-line redesign
  - Saves time and money!

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Uncertainty and Disturbance Rejection

- **Uncertainty and disturbances**
  - Plant-model mismatch unavoidable
  - Disturbances always acting on system
  - Noisy measurements

- Recall: Aim of *feedback* control is to minimise effect of uncertainty and disturbances

- Predictive control allows one to reject measured and unmeasured disturbances
  - Achieves this through *feedback*
What Is Predictive Control?

- Predictive Control = *Practical Optimal Control*
- At each time instant, a predictive controller
  - uses a *current measurement* of the output and
  - an internal *model* of the system to
  - compute and implement a *new control input* that
  - minimises some *cost function*, while
  - guaranteeing that *constraints* are satisfied
- Usually the control input is implemented in a *receding horizon* fashion
- We have *feedback*, because we are computing a *new input* for each *new measurement*
The Receding Horizon Principle

1. Obtain measurement of current output
2. Compute optimal input sequence over a finite horizon
3. Implement only first part of input sequence
4. Obtain new plant measurement and go to step 2

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Computational Speed And Applications

- Finding an optimal input sequence requires a fast computer
- Historically, predictive control has been applied to “slow” processes:
  - Sample time $T_s$ of seconds to hours
  - Petrochemical and process industries, pulp and paper
- With advances in hardware and algorithms:
  - Computation of 1min in 1990, now takes less than 1s
  - Experts say same computation should take less than 1ms!
- Predictive control is being applied to “fast” processes:
  - Traction and engine control in cars
  - Aerospace applications
  - Autonomous vehicles
  - Electricity generation and distribution
Early History of Predictive Control

- First industrial developments about 1970:
  - Adersa France: Richalet (*Automatica* 1978)

- Patents:
  - Martin-Sanchez (Spain), 1976
  - Prett, Ramaker, Cutler (Shell), 1982

- Academics:
  - Propoi (1963)
  - Kleinman (1970)
  - Kwon and Pearson (1975)
  - Rouhani and Mehra (1982)
  - Clarke *et al.* (1987)
A Rose By Any Other Name...

- Dynamic Matrix Control (DMC)
- Extended Prediction Self Adaptive Control (EPSAC)
- Generalised Predictive Control (GPC)
- Model Algorithmic Control (MAC)
- Predictive Functional Control (PFC)
- Quadratic Dynamic Matrix Control (QDMC)
- Sequential Open Loop Optimization (SOLO)

**Generic names:**
- Model Predictive Control (MPC)
- Model Based Predictive Control (MBPC)
- Receding Horizon Control (RHC)
Summary

- Multivariable, difficult and nonlinear systems
- Optimality of operation
- Importance of constraints
- Flexibility of performance specifications
- Predictive control = Practical optimal control
- Internal model to predict plant behaviour
- Solve optimization problem to compute control
- Receding horizon principle
- Feedback allows us to reject disturbances