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# 4F3 – Predictive Control

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## Lecture 1

### Introduction to Predictive Control

Dr Eric Kerrigan

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## Outline Of Course

- Introduction to predictive control
- Digital state space control theory
- Unconstrained predictive control
- Predictive control with constraints
- Set-point tracking and offset-free control
- Stability and feasibility in predictive control -  
Dr Jan Maciejowski
- Case study by industrial speaker – Dr Paul Austin

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# Outline Of Lecture 1

- Why predictive control?
    - Multivariable systems
    - Nonlinear and “difficult” systems
    - Constraints are important
    - Optimal operation
    - Flexible performance specifications
    - Disturbance rejection
  - The receding horizon principle (no maths)
  - History of predictive control
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# Success Of Predictive Control

- What other control techniques are out there?
    - PID (2<sup>nd</sup> year) – by far the most successful!
    - LQR/LQG (4F2)
    - $H_{\infty}$  control (4F2)
    - 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
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# 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



# Nonlinear Systems

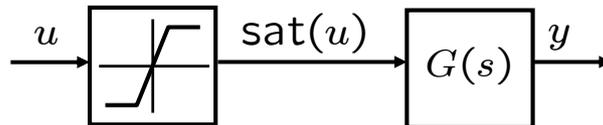
- Differential equations are often nonlinear (4F3)

- Aeroplane dynamics
- Chemical reactions

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

- Saturation on variables

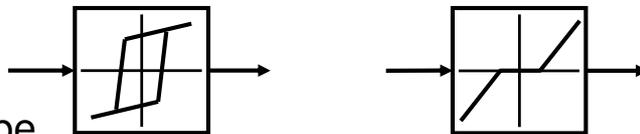
- Ailerons and rudders
- Valves



$$\dot{x} = Ax + B\text{sat}(u)$$

- Hysteresis and deadzones

- Relays
- Valves



- Predictive controllers can be designed for nonlinear systems

# 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



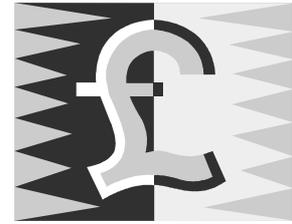
- Most control methods address constraints *a posteriori*, e.g.

- Anti-windup
- Clever tricks
- Trial and error



- Predictive control addresses constraints *a priori* and allows constraints to come “out of the closet”

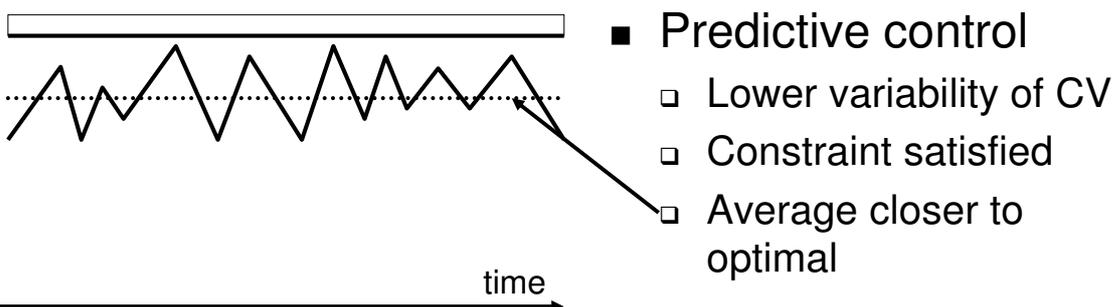
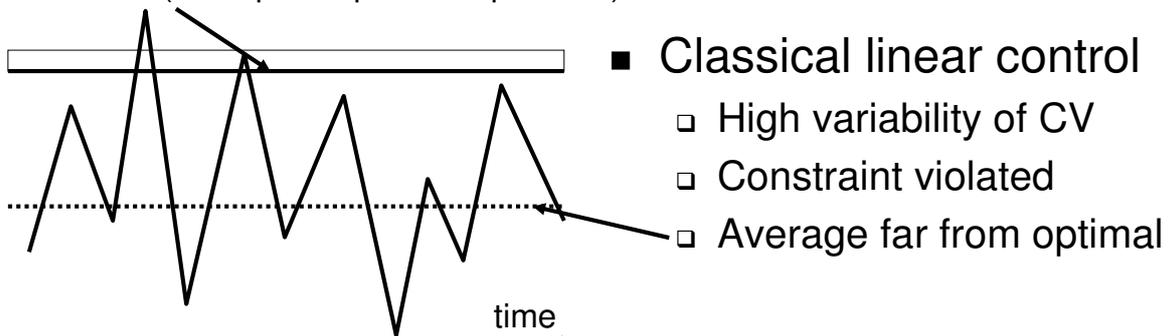
# Optimal Operation



- 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

## Optimal Operation Close To Constraints

Constraint (and optimal point of operation)



# 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!



# Uncertainty and Disturbance Rejection

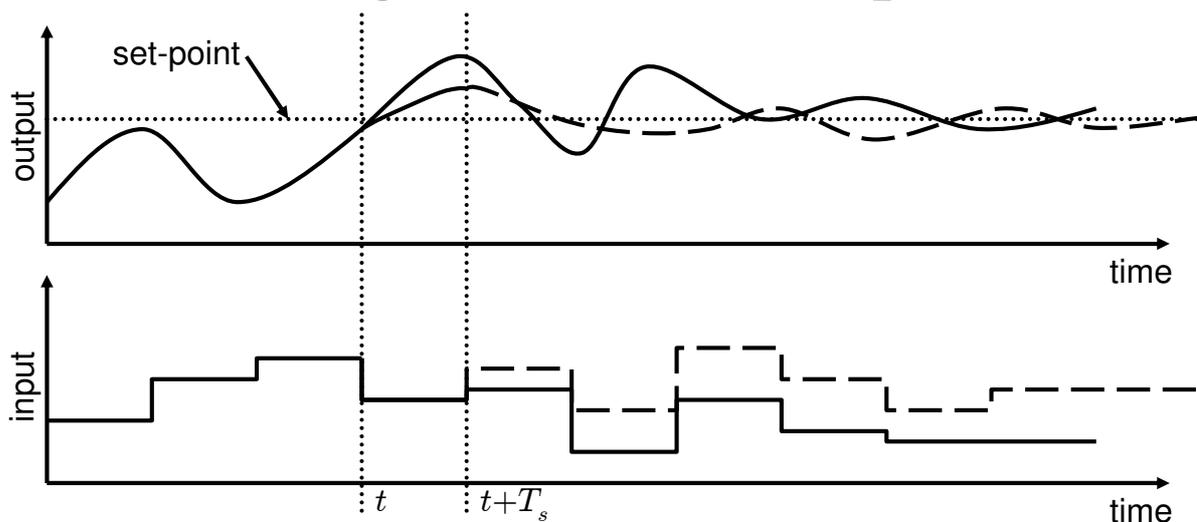
- Uncertainty and disturbances
  - Plant-model mismatch unavoidable
  - Disturbances always acting on system
  - Noisy measurements
- Recall: Aim of *feedback* control is to minimise effect of uncertainty and disturbances
- Predictive control allows one to reject measured and unmeasured disturbances
  - 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

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# Early History of Predictive Control

- First industrial developments about 1970:
  - *Shell Texas: Cutler et al. (Proc. JACC 1980)*
  - *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)

# What Is In This Course?

- In:
  - Linear systems with input saturation (common nonlinearity)
  - Linear inequality constraints on the states and outputs (due to performance/safety considerations, not physical)
  - Discrete-time predictive control
  - Continuous state/input systems
- Out:
  - General nonlinear systems
  - Robust predictive control
  - Continuous-time and sampled-data predictive control
  - Discrete and hybrid systems

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# Summary

- Multivariable, difficult and nonlinear systems
- Optimality
- Importance of constraints
- Predictive control = Practical optimal control
- Internal model predicts plant behaviour
- Solve optimal control problem with computer
- Receding horizon principle
- Reject disturbances using feedback