Quantitative Process Control Theory

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Chapter 1 Introduction

1.1 A Brief History of Control Theory

Development of Control Theory

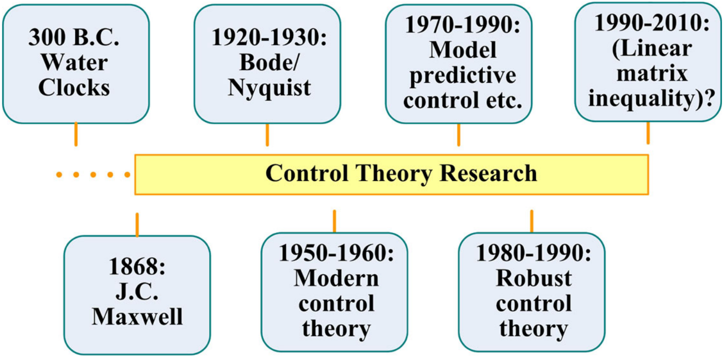

Figure: Selected historical developments of control systems

The birth of control theory:
Maxwell's paper provided the first rigorous mathematical analysis of a feedback control system for a centrifugal governor

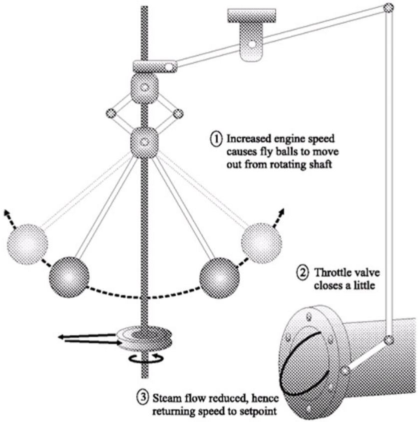

Figure: Fly ball governor (From Goodwin's ppt)

Classical Control Theory

During the World Wars, the development of feedback control systems became a matter of survival.

Tools: Frequency domain techniques

Important results:

- Bode stability criterion (1927)
- Nyquist stability criterion (1932)
  (An indispensable means for analyzing and designing control systems even today)

Problems that need to be clarified for deeper and more comprehensive studies. For example:

1. Mathematically, what is the objective of control system design?
2. How is the control system optimized in the design?

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Modern Control Theory

In the 1960's, modern control theory established itself as a paradigm for automatic controls design in the U.S.

Tools: State space method

Important results:

- Linear Quadratic (LQ) regulator (Kalman, 1960)
  (The idea controls the control theory research in the past half centenary)
- Kalman filter (Kalman, 1960)

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2. How to treat the model uncertainty problem?
   (which is treated in classical control theory with notions like the gain margin and phase margin)

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Robust Control Theory

Model uncertainty is fully considered in robust control theory.
Robustness: Insensitive to the model uncertainty.
Tools: Combined frequency domain and state space method
Important results:

- Youla parameterization (Youla et al., 1976)
  (Important idea in modern design methods)
- H_∞ control (Zames, 1981)
- State space solution to the H_∞ control (Doyle et al., 1989)

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Linear Matrix Inequalities

A powerful theoretical tool. Perhaps the hottest direction during 1990s and 2000s in control area. Numerous papers were published with this topic in top journals.

Tools: State space method

Important results:

- Interior-point method in convex programming (Nesterov and Nemirovsky, 1994)
- Linear mateix inequalities in control (Boyd, et al., 1994)

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Model Predictive Control

Some similar algorithms used in process industries.
Process control: Control temperature, pressure, flow rate, level, consistence, etc., which are usually appears in industrial processes
Tools: Input-output method (frequency domain or polynomial)
Important results:

- Model Algorithmic Control (Richalet et al., 1978)
- Dynamic Matrix Control (Culter and Remaker, 1979)
- Internal model control (Morari, 1982; 1989)
  (Explains some important problems of control system design in a simple and direct framework)

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1.2 Design of Feedback Control Systems

The Most Elementary Feedback Control System

Three components:

- A plant(Usually, the actuator is lumped in with the plant)
- A sensor to measure the output of the plant
- A controller (Manipulate the plant input so that the error between the real output and the desired output is driven toward zero)

Plant considered in this book: Linear plants

Linearity: The principle of superposition applies

The principle of superposition: The response produced by the simultaneous application of two different forcing functions is the sum of the two individual responses

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An Example of Control Systems

Plant: Paper-making machine
Plant input: Flow rate of stock
Plant/system output: Basis weight
System input/desired output: Reference

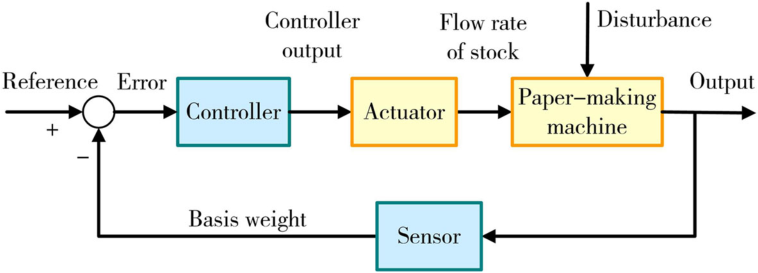

Figure: Paper-making process control system

Design Procedure

The procedure generally involves two steps:

1. Analysis—What dynamic behavior does the plant have? What is the control objective?
2. Design—How to design the controller to satisfy the requirement?

The procedure may require judgment and iteration.

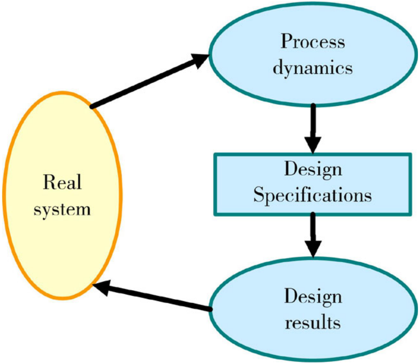

Figure: Design procedure

Models

Models: Describe the dynamic behavior of a plant

Nominal plants: The model used for control system design
Uncertainty: Difference between the nominal and the real plants
Uncertain plant family: Nominal plants plus uncertainty

Time delay: The input cannot instantly reflected in the output

Compared with other systems, the uncertainty problem is more prominent in industrial systems. This is due to not only technical reasons, but also economical reasons

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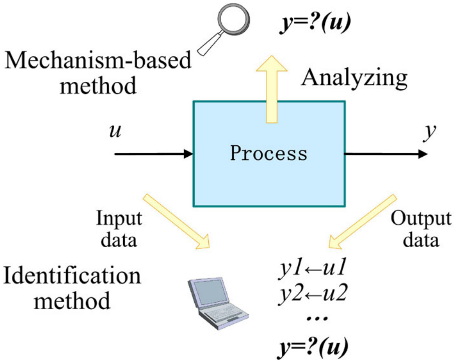
Two modelling methods:

- Mechanism-based method—Build the model by applying the laws of physics, chemistry,etc
- Identification method—Build the model from the measured input-output data



Objectives

Two common objectives based on operating features:

1. Regulator problem—To keep the system output close to some equilibrium point.
2. Servo problem—To keep the difference small between the output of the system and a prescribed reference.

In most cases, the design for the regulator problem is identical to that for the servo problem.

Features of process control systems: The reference does not change often

The main problem in process control systems: The regulator problem

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Design

Two methods to design a controller:

1. Empirical method—Choose a controller first, and then adjust it by rules of thumb (Referred to as controller tuning).
2. Model-based method—Both the structure and parameters of the controller are derived based on models (Experience is necessary even in this method).

In industrial systems, a controller with parameters that cannot be adjusted is seldom used, because:

1. It's a challenge to obtain the information about uncertainty
2. The operating point of the system may offset or change
3. The design requirement may be changed after the system comes into operation

Commonly used controller: Fixed structure and adjustable parameters

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1.3 Consideration on Control System Design

Problems in Some Advanced Control Theories

Many theories were proposed for control system design:
LQ control, H_∞ control, and so on

Problems for some advanced control theories

1. These theories depend on empirical methods or trial and error methods in choosing weighting functions
2. Both the design procedure and the result are complicated for understanding and using, especially for plants with time delays)
3. The controller cannot be designed or tuned for quantitative engineering indices (such as overshoot or stability margin)

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Development of the New Theory

Several problems considered in the new theory:

1. How can the choosing of weighting functions be simplified?

Situation: Only empirical methods or trial and error methods are available for choosing weighting functions.

Effect: Different designers will obtain different controllers even the same method is used.

New theory: The designer is not required to choose weighting functions. The function of weighting functions is substituted by introducing a filter

Development of the New Theory (ctd.1)

2. Can the control system with time delays be analytically designed by the optimal method?

Situation: Empirical methods cannot design controllers optimally, while optimal methods are numerical methods.

Merit of the analytical design: The designer can use formulas to design a controller. The design task is significantly simplified.

New theory: Aanalytical optimal solution is given.

Development of the New Theory (ctd.2)

3. How is the order of the optimal controller related to the order of the plant?

Situation: The controller designed by optimal design methods is usually of high order.

Expectation: It is desirable to know the relationship between the order of the optimal controller and the order of the plant.

New theory: There is a direct relationship between the controller order and the plant order.

Development of the New Theory (ctd.3)

4. How is the new design theory related to classical performance indices?

Existing problems: The performance index of modern control theory has little relationship with engineering design requirements (Overshoot, rise time, stability margin, etc.).

Effect: The modern control theory was not widely adopted in industrial systems.

New theory: The quantitative relationship between the optimal performance indices and engineering performance indices is built based on the performance degree.

Development of the New Theory (ctd.4)

5. Can the performance and the robustness be easily tuned?

Existing problems: It is difficult to make a clear and reasonable tradeoff between nominal performance and robustness. In addition, the design requirement may be changed and the uncertainty may be offset.

Expectation: Instead of re-designing the control system, engineers hope to tune the system to satisfy the design requirement in these cases.

New theory: A simple and effective tuning method is provided to solve the problem.

Development of the New Theory (ctd.5)

6. Is the design method applicable to different input signals?

Situation: Many design methods have a hidden assumption; that is, the input signal is a step.

Expectation: It is desirable that the developed design method works for other signals, like ramps.

New theory: The new theory provides a design method applicable to different input signals.

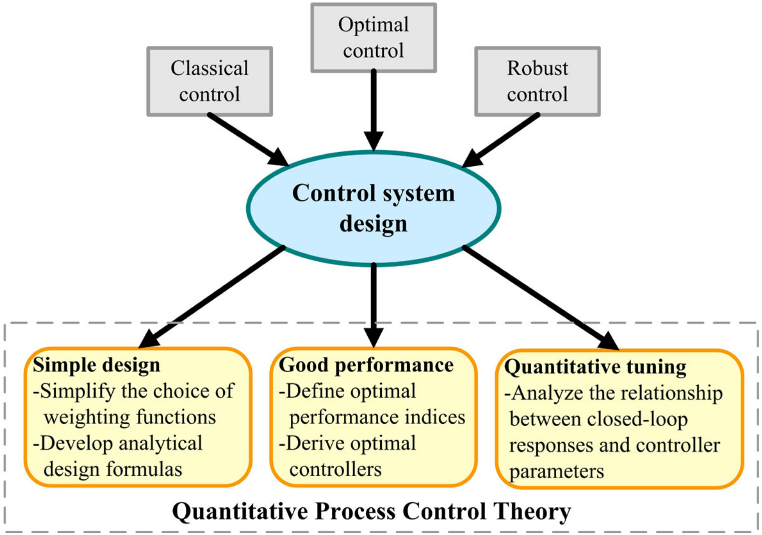
New Theory:
Quantitative Process Control Theory

Methodology: Extending the ideas and methods of classical control theory, optimal control theory, and robust control theory.

Goal

- To simplify the design procedure on the premise of ensuring good performance
- To design controllers for quantitative performance requirements

Features: No-weight, analytical, and quantitative
This makes it possible to deaign a controller in several minutes.


Classical control
Optimal control
Robust control
Control system design
Simple design
-Simplify the choice of weighting functions
-Develop analytical design formulas
Good performance
-Define optimal performance indices
-Derive optimal controllers
Quantitative tuning
-Analyze the relationship between closed-loop responses and controller parameters
Quantitative Process Control Theory

Applications to Autotuning Control

Autotuning: An important method for enhancing the automatic level of a control system.

Procedure: and calculates controller parameters accordingly.

- Identification—The controller conducts its own process behavior test
- Parameter computation—The controller parameters are computed accordingly based on the obtained model

Requirement: As all of these works are finished in the field computer, design formulas are necessary for the parameter computation.

The new theory is particularly suitable for autotuning control.

1.4 What This Book is About

Some Hints

Mathematical tools: **Input-output method** (Frequency domain method or polynomial method)

- The input-output method is closely related to classical methods and easy to understand
- The resulting controllers are easy to implement and use

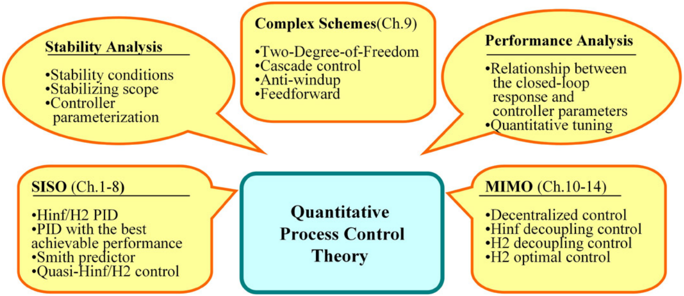
Plants considered: Plants with time delays

Main results in the book: **A series of formulas for controller design**

Boxes in examples: The plant model and the analytical controller

Stars in exercises: The knowledge about the state space method is needed

Main Contents of This Book



A unified framework: The SISO material can be regarded as a special case of the MIMO material

References for Reading

Morari, M. and E. Zafiriou, Robust Process Control, Prentice Hall, 1989

Doyle, J.C., B. A. Francis, and A. R. Tannenbaum. Feedback Control Theory, McMillan Company, 1992

End of Chapter 1