Black Boxes & White Noise
The Evolution of Automatic Control

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1. Introduction
2. Early Ideas
3. A Discipline Emerges
4. The Second Wave
5. Conclusions
Application Packages
Mould Level Control, Continuous Steel Casting, ±3 mm
Natural Science and Engineering Science

Many similarities but also differences

**Natural Phenomena**
- Analysis
- Isolate phenomena
- Simplicity
- Basic laws

**Technical Systems**
- Synthesis
- Interaction
- Complexity
- System principles
SSI, MSI, LSI, VLSI

4 lines = 50u
1mm

4 lines = 10u
5mm

4 lines = 5u
10mm

4 lines = 0.5u
20mm

CHIP SIZE

COVENT GARDEN
TRAFALGAR SQUARE

1km
SSI
c 1963

25km
MSI
c 1978

250km
LSI
c 1985

2000km
VLSI
c 199?
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Industrial Process Control

Windmills Mead 1787

Steam engines
  Watt, Boulton 1788
  Maxwell 1868
  Routh 1875

Water turbines
  Stodola 1893
  Hurwitz 1895
PID Control

\[ u(t) = k \left( e(t) + \frac{1}{T_i} \int_0^t e(s) \, ds + T_d \frac{de}{dt} \right) \]

Honeywell
Taylor Instrument
Leeds & Northrup
Foxboro
Flight Control

The Wright Brothers  1903
Sperry  1912
Fully Automatic transatlantic flight 1947
Apollo  1969
Minorsky 1922

It is an old adage that a stable ship is difficult to steer.
### Telecommunication

<table>
<thead>
<tr>
<th>SYSTEM</th>
<th>DATE</th>
<th>CHANNELS PER PAIR</th>
<th>LOSS IN DB (3000 MI)</th>
<th>REPEATERS (3000 MI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st Transcontinental</td>
<td>1914</td>
<td>1</td>
<td>60</td>
<td>3–6</td>
</tr>
<tr>
<td>2nd Transcontinental</td>
<td>1923</td>
<td>1–4</td>
<td>150–400</td>
<td>6–20</td>
</tr>
<tr>
<td>Open Wire Carrier</td>
<td>1938</td>
<td>16</td>
<td>1000</td>
<td>40</td>
</tr>
<tr>
<td>Cable Carrier</td>
<td>1936</td>
<td>12</td>
<td>12000</td>
<td>200</td>
</tr>
<tr>
<td>First Coaxial</td>
<td>1941</td>
<td>480</td>
<td>30000</td>
<td>600</td>
</tr>
</tbody>
</table>
**The Feedback Amplifier**

Black's patent 1928

Granted 1937

“Singing” = Instability

Nyquist 1932

Bode 1945

Network Analysis and Feedback Amplifier Design

\[
\frac{V_2}{V_1} = - \frac{R_2}{R_1} \cdot \frac{1}{1 + \frac{1}{A} \left(1 + \frac{R_2}{R_1}\right)}
\]
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A Discipline Emerges

Industrial Process Control
Telecommunications
Flight Control
Mathematics

Principles
Theory
Design Methodology
Applications
War Pressures

National Defense Research Committee
MIT Radiation Laboratory
MIT Servomechanism Laboratory
MIT Instrumentation Laboratory
MIT Lincoln Laboratory
The Black Box Concept

Input

Output

Abstraction
Information hiding
The Black Box View of Dynamical System

- Linearity
- Superposition
- Sinusoids
- One pair suffices
The Notion of Transfer Function

\[ G(s) = \int_{0}^{\infty} e^{-st} g(t) \, dt = \mathcal{L}(g) \]

\[ G(s) = \frac{\mathcal{L}\{y\}}{\mathcal{L}\{u\}} \]
System Principles

Feedforward

Feedback

Combination
Two Paradigms

Feedback
Open loop
Acts only on deviations
Market driven
Unmeasurable disturbance
Less accurate model

Feedforward
Closed loop
Act before deviations occur
Planning
Measurable disturbance
Accurate model
Servomechanism Theory

Foundations
Complex variables
Laplace transforms

System Concepts
Feedback
Feedforward

Design methodology
Frequency response
Graphical methods

Analog simulation
Implementation
The Second Wave

Feedback from applications
Challenging problems
New technology
New ideas
Key Elements

Reexamination of fundamentals
Vital interaction with other disciplines
Theory to match new technology
Two views of Dynamical Systems

External Description
Electrical engineering
Input/Output
Black Box

Internal descriptions
Mechanical Engineering
The notion of state

\[
\frac{dx}{dt} = f(x,u) \\
y = g(x,u)
\]
“Modern” Control Theory

- Optimal control
- Computer control
- Stochastic control
- Robust control
- CACE
- System identification
- Adaptive control
- Intelligent control
Optimal Control

- Euler: 1707–1783
- Lagrange: 1736–1813
- Pontryagin: 1962
- Hamilton: 1805–1865
- Jacobi: 1804–1851
- Bellman: 1957
Modeling Disturbances

Power spectra
White noise
Innovations
Stochastic Control Theory

- Filtering and prediction
- Merger of calculus of variations and theory of random processes
- Decision making under uncertainty
- Industrial process control

![Diagram showing probability density, test limit, set points for regulators with low and high variance, and process output.]{LUND INSTITUTE OF TECHNOLOGY}
System Identification

Model of process dynamics and disturbances
Control of Basis Weight

Wet basis weight

Set point of stuff gate level
Adaptive Control

Design

Estimator

Process

Regulator

Regulator parameters

$r$

$u$

$y$
Dual Control

- Control actions should be both directing and investigating
- Consequences for decision making decisions under uncertainty
Two Principles

Certainty Equivalence  (H. Simon 1956)
Make the best estimate act as if it was true.

Dual Control
Control should be investigating as well as directing.
Computer Aided Control Engineering

How to disseminate complicated technology?
Conceptual simplicity computational sophistication
Combine human intuition with computational power
Nice way to package theory
Computer Control

[Diagram showing the increase in the number of computers from 1960 to 1990, with two lines indicating 'Process control' and 'All computer'.]
Control Design & Process Design
The Internal Model Principle
Applications

- Energy generation
- Energy transmission
- Process control
- Discrete manufacturing
- Instrumentation
- Telecommunication
- Transportation
- Heating, ventilation, aircondition
- Entertainment
- Physics
- Biology
- Economics
Mission Critical

Flight Control
Space flight
Automotive
CD player
Camcorder manufacturing
The Mercedes A-class

Automatic control gives extra freedom to the designer

Unstable behavior improved by
Electronic Stabilization Program (ESP)
Control and Economics

Committee on Policy Optimisation HSO 1978

To consider the present state of development of optimal control techniques as applied to macro-economic policy. To make recommendations concerning the feasibility and value of applying these techniques within Her Majesty’s Treasury.
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Some Challenges

The gap between theory and practice
“Intelligent” systems
Man–machine interfaces
Technology / society interfaces
Academic positioning
Real World

Mathematical Modeling
- Energy
- Transportation
- Communication
- Manufacturing
- Instrumentation
- Entertainment
- Biology
- Economics

Automatic Control
- Analysis
- Simulation
- Synthesis

Implementation

Commission

Operation
Conclusions

A glimpse of an emerging field
Automatic control is pervasive
Some system principles
Many challenges ahead