QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

TWO THOUSAND YEARS OF CONTROL AND AUTOMATION

BRIAN D. O. ANDERSON

RESEARCH SCHOOL OF INFORMATION SCIENCES & ENGINEERING

AUSTRALIAN NATIONAL UNIVERSITY

- PRE-SCIENTIFIC AUTOMATION AND CONTROL
- THE SCIENTIFIC PRE-COMPUTER PERIOD
  (1900 - 1955)
- SOME MAJOR DEVELOPMENTS
  (1955 - 2000)
- WHAT OF THE FUTURE?

QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

- PRE-SCIENTIFIC AUTOMATION AND CONTROL
  - » Automation Applications and Control Science Problems
  - » Water flow
  - » Fan-Tails and Windmills
  - » Steam Engines
  - » Telescopes and Airy
  - » The Stability Problem

- THE SCIENTIFIC PRE-COMPUTER PERIOD
  (1900 - 1955)

- SOME MAJOR DEVELOPMENTS
  (1955 - 2000)

- WHAT OF THE FUTURE?

AUTOMATION APPLICATIONS AND CONTROL SCIENCE PROBLEMS

QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

- The applications areas
  - » Water Flow
  - » Windmills
  - » Steam Engines
  - » Telescopes

- The control science problems

  Securing dynamic stability

  Securing zero steady state

  error given constant disturbances

WATER FLOW

QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

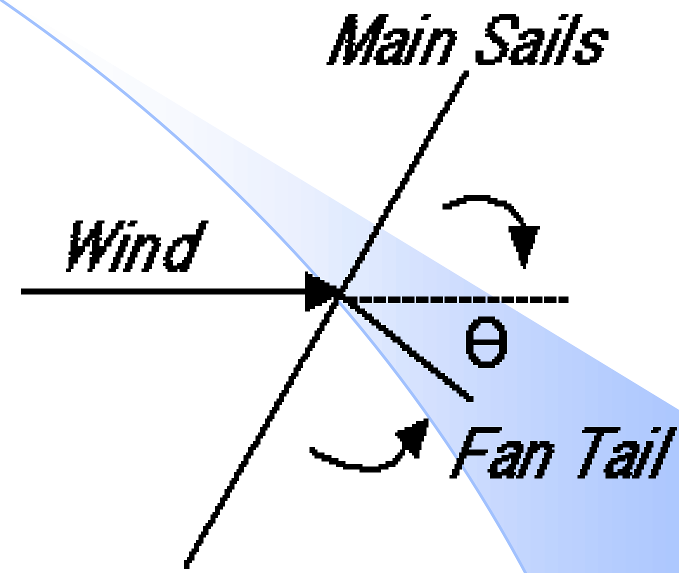
Some 2000 years ago, one could

- Shut off cisterns automatically
- Use water flow as power source, with flow adjustment giving power adjustment

FAN-TAILS AND WINDMILLS

QuickTime™ and a Photo - JPEG decompressor are needed to see this picture.

- AIM:
  Turn Windmill structure to make sails face the wind



- SOLUTION:
  Use fantail (auxiliary rotor) at right angles to main sails. Fan used to turn structure

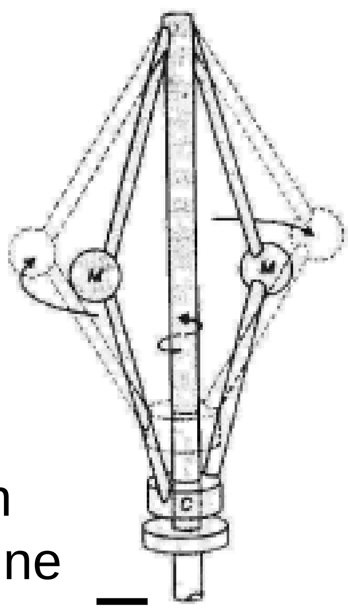
OTHER WINDMILL CONTROLS:

QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

- Centrifugal governor using flyballs

  Balls rise $\rightarrow$ partial furling of sails

  $\rightarrow$ decrease in speed



driven
by engine

Flyball Governor

- Governor to adjust gap between stones

- Governor to adjust rate of grain supply to stones

STEAM ENGINES

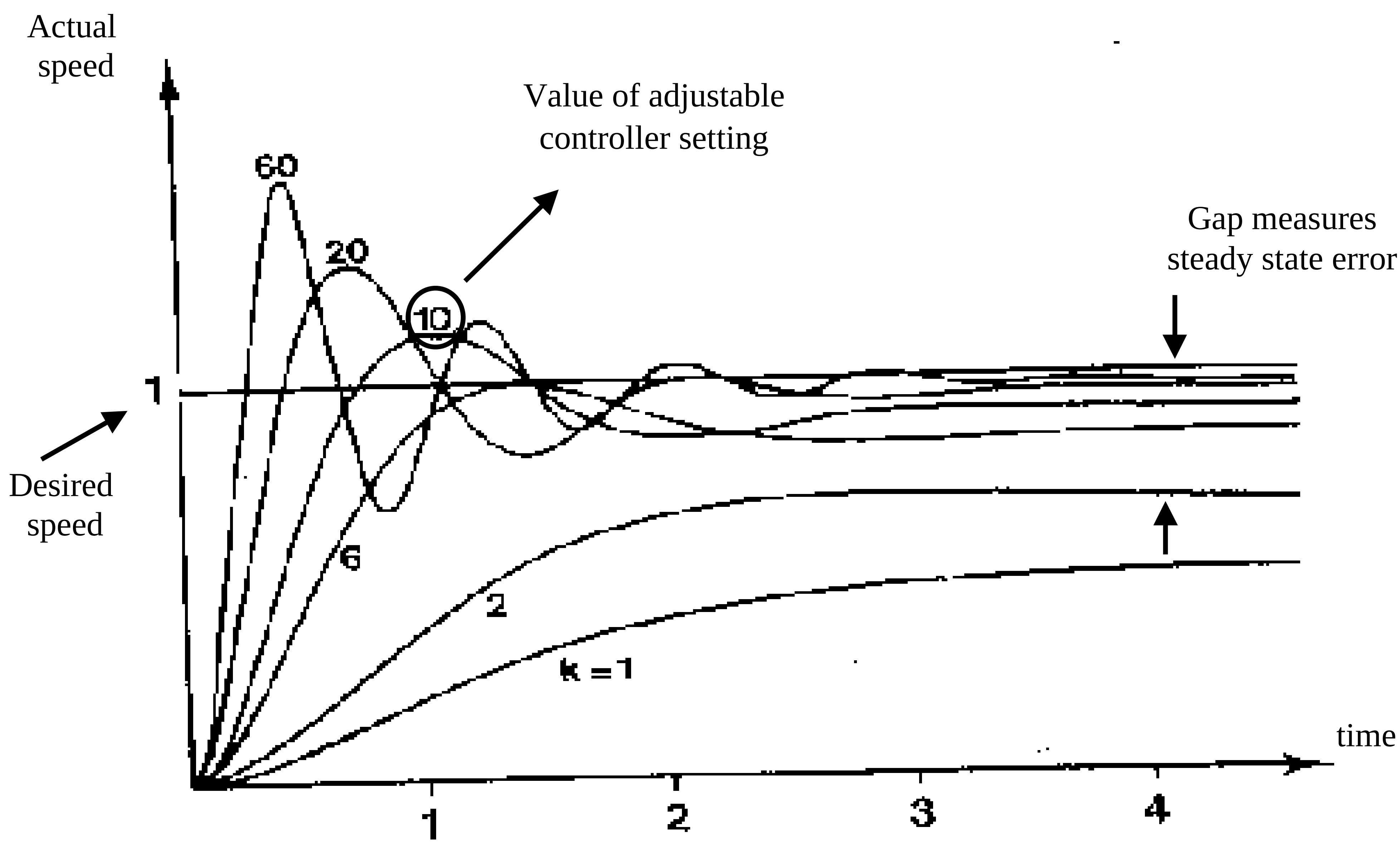
QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

- James Watt adapted flyball governors used on windmills to steam engines

- 75000 Watt governors in UK in 1869 highlight the problems. Issue of offset error, overshoot with too high gain became understood experimentally

STEAM ENGINES cont.

QuickTime™ and a Photo - JPEG decompressor are needed to see this picture.



TELESCOPES & AIRY

QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

- Airy: (1801 - 1892), Astronomer Royal, 500 papers, 11 books
- His Problem: Rotate a telescope uniformly
- Available Technology: Flyball governor
- The Control Problem: Understand instability
- His Contribution: Experimental and theoretical (using celestial mechanics ideas)

TELESCOPES & AIRY

- Described instability phenomenon

- Showed could analyze via differential equation

$$\frac{d\theta}{dt}^{2} + \frac{a}{\mathrm{Sin}^{2}\theta} - \frac{2q}{b}\cos\theta = c$$

[θ moves round a nominal value]

- Showed could adjust dynamics to get stability

THE STABILITY PROBLEM

QuickTime™ and a Photo - JPEG decompressor are needed to see this picture.

When does the polynomial

$s^n + a_1 s^{n-1} + \ldots + a_n$

have all its roots with negative real parts?

Stream 1

French mathematicians
Cauchy 1831
Sturm 1835
Hermite 1856

Uninterpreted by engineers

Stream 2

English scientists/engineers
Maxwell 1857
- Saturn Rings
- (4th order systems)
- Governors. Complex roots
- (3rd order systems)

Routh 1877
- Drew on Cauchy, Sturm, Maxwell, Airy (father in law)
- Routh Table

Stream 3

Swiss scientists/engineers
Stodola- first control engineer academic
- drew on Russian Vishnegradsy
- Water turbine control
  (3rd order, 7th order)

Hurwitz 1895

- PRE-SCIENTIFIC AUTOMATION AND CONTROL
  (17th - 19th Centuries)

QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

- THE SCIENTIFIC PRE-COMPUTER PERIOD
  (1900 - 1955)

  » The Basic Paradigm of the Feedback Loop
  » Nyquist Criterion
  » High Loop Gain
  » Overall Design Flavour and Shortcomings
  » Other Developments

- SOME MAJOR DEVELOPMENTS
  (1955 - 2000)

- WHAT OF THE FUTURE?

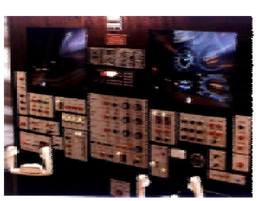
WHAT IS A TYPICAL CONTROL PROBLEM ?

QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

	Physical Entity	Response	Excitation	How Achieved
	Car Engine	Speed	Fuel Flow	Accelerator
	Electric Heater	Temperature	Electric Power	Switch
	Aircraft	Attitude	Hydraulics to control surface	Controls stick plus links

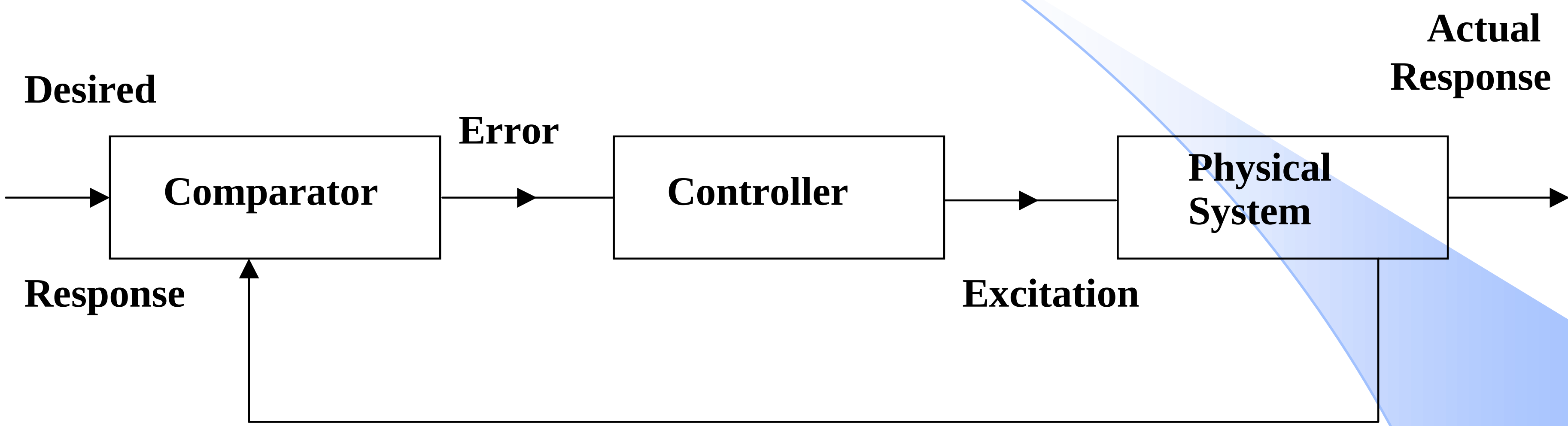
QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

CLOSED-LOOP CONTROL

	Physical Entity	Excitation	Closed-Loop approach
	Car Engine	Fuel Flow	Cruise Control
	Electric Heater	Electric Power	Thermostat
	Aircraft	Hydraulics to Control surfaces	Automatic pilot Blind landing etc

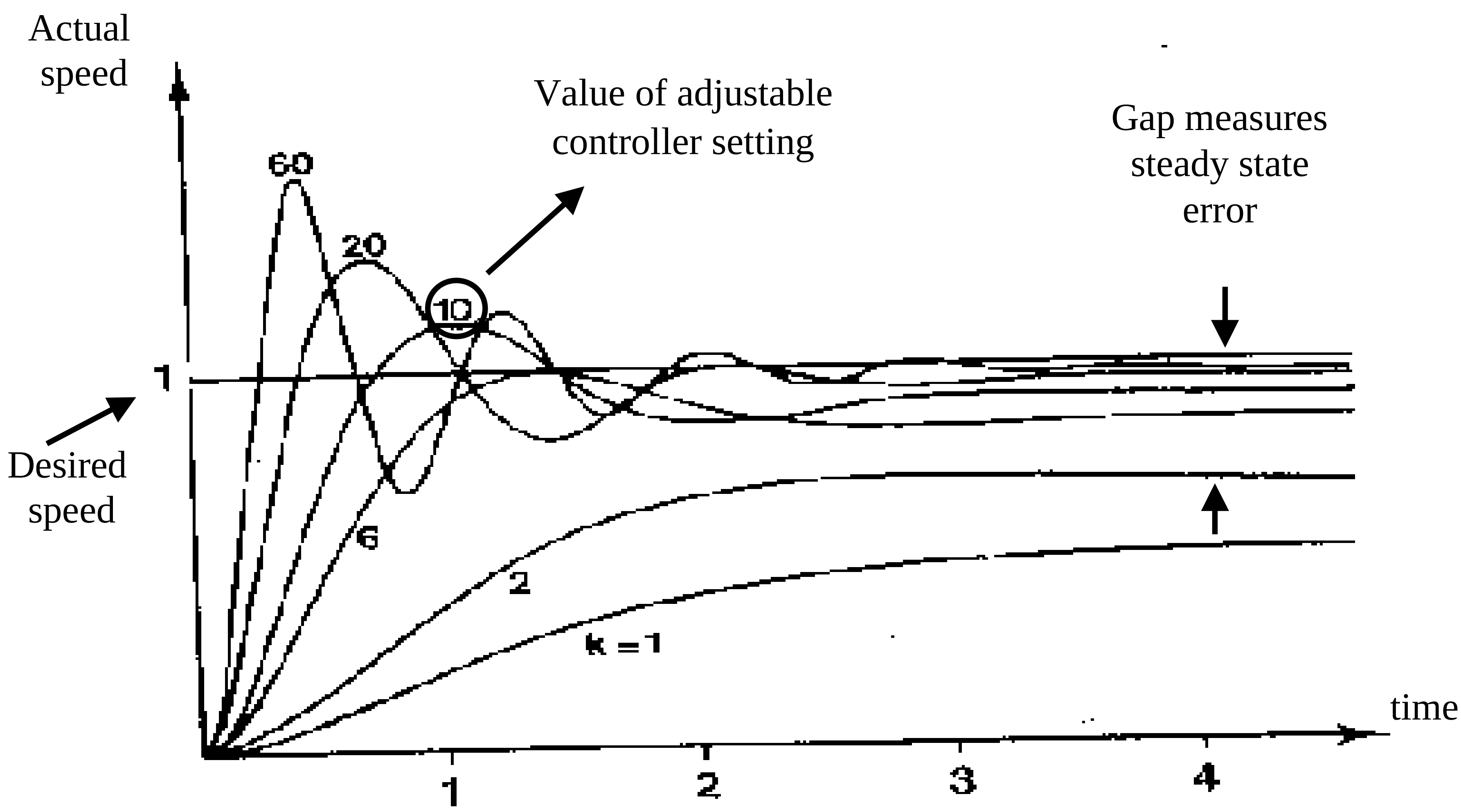
CLOSED-LOOP CONTROL

QuickTime™ and a Photo - JPEG decompressor are needed to see this picture.



ISSUES: **Overcorrection/instability**

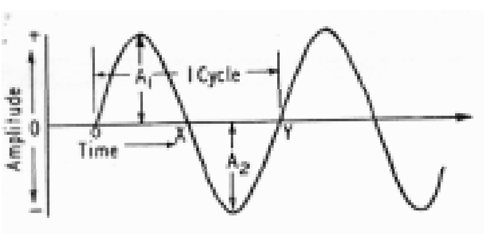
Steady State Error


Actual speed
Value of adjustable controller setting
Gap measures steady state error
60
20
10
6
2
k = 1
1
Desired speed
time
1
2
3
4

NYQUIST CONTRIBUTION

QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

- Airy and Maxwell modelled physical system with differential equations
- Nyquist and others modelled physical systems with experimental data (usually represented graphically)



sine wave → **Physical System** → sine wave

- Output is generally time-shifted and has amplitude changed, with time-shift and amplitude change dependent on frequency

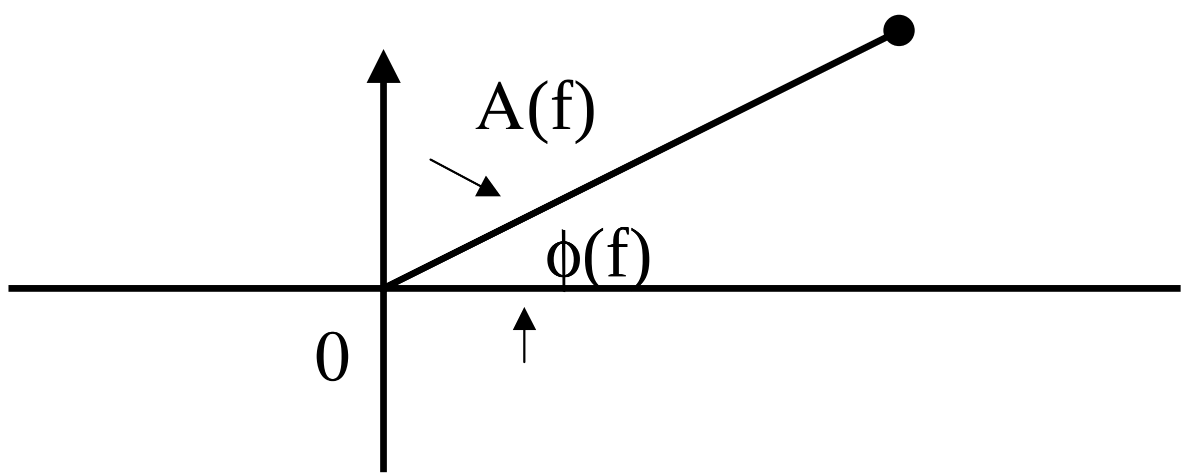
Nyquist said:

QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

- Let $$A(f) = \frac{\text{output amplitude}}{\text{input amplitude}} \text{ at frequency } f$$

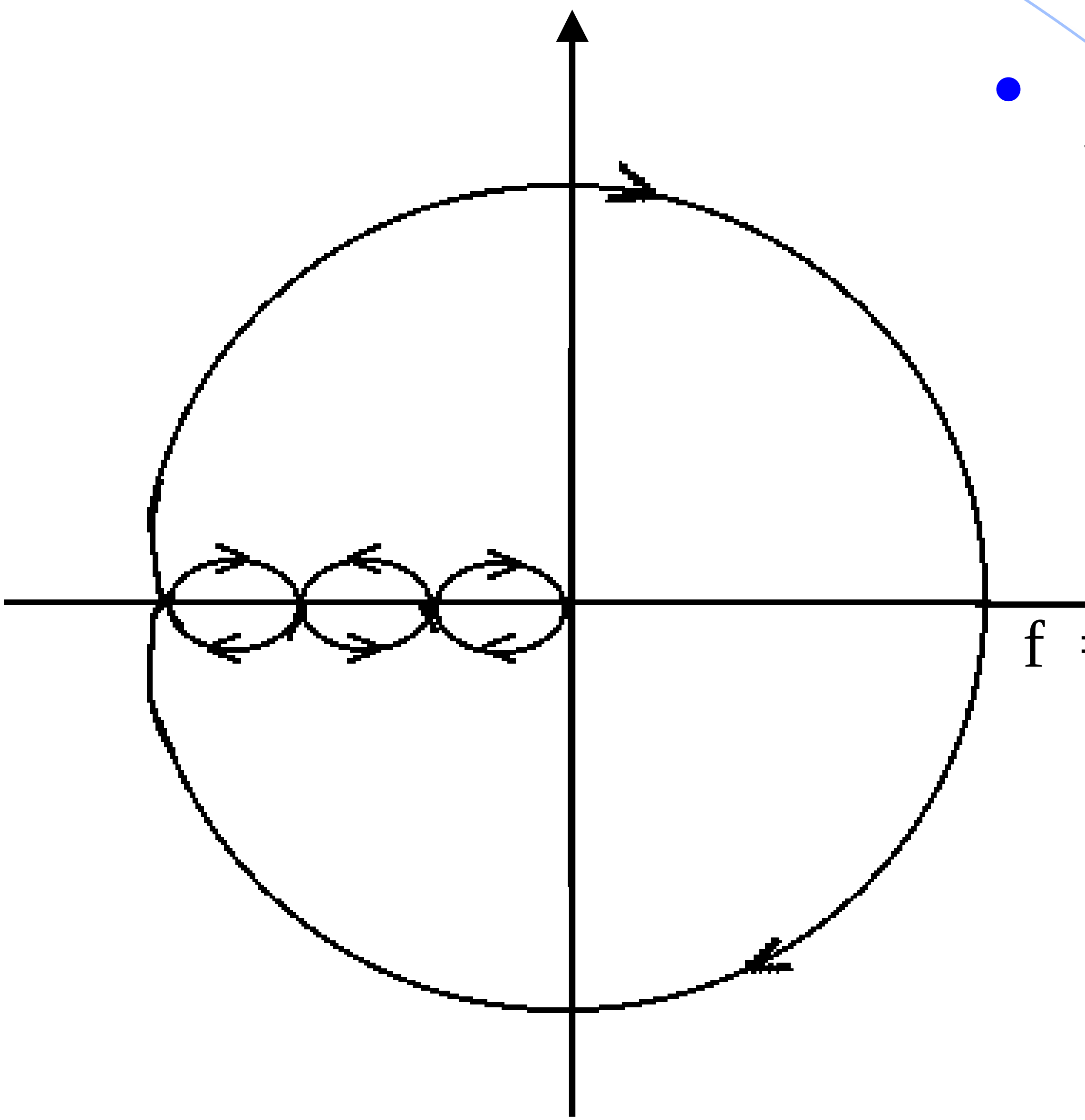
  $$\phi(f) = \text{shift in angle of output sine wave relative to input}$$

- Plot the point at distance A(*f*) from 0 making angle ϕ(*f*) with horizontal axis



- Do this for all *f*

QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

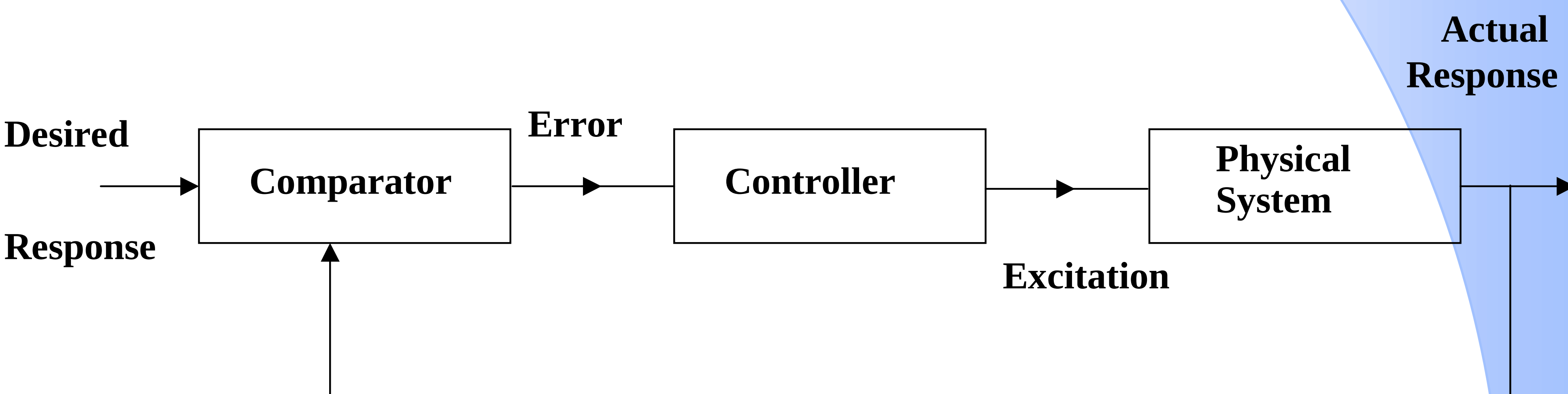


- The general shape tells you about
  - stability or instability
  - overshoot
  - steady state error

QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

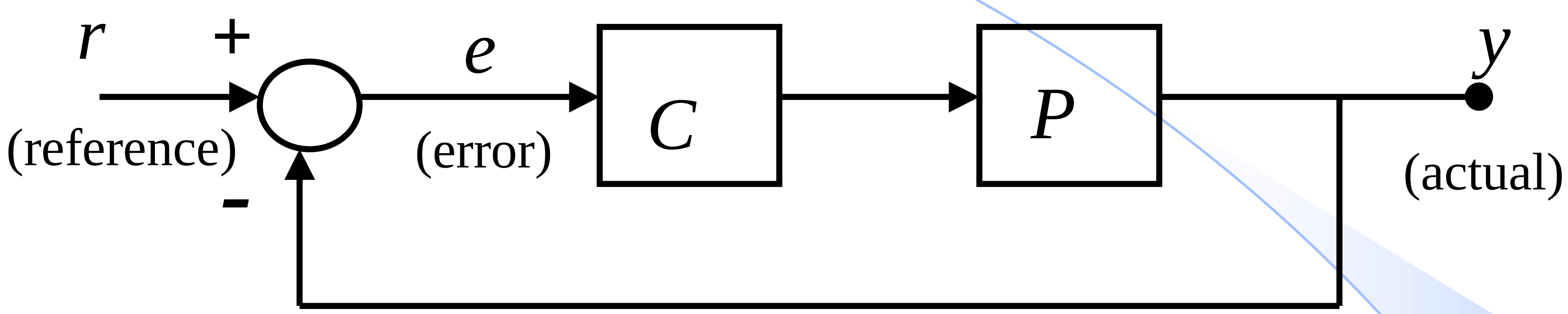
- Intuition: Feeding back output in phase with input (positive feedback) can reinforce and even produce instability.

- The general shape tells you what sort of amplitude adjusting and time-shifting properties the controller should have at each frequency to get nice behaviour



HIGH LOOP GAIN

QuickTime™ and a Photo - JPEG decompressor are needed to see this picture.



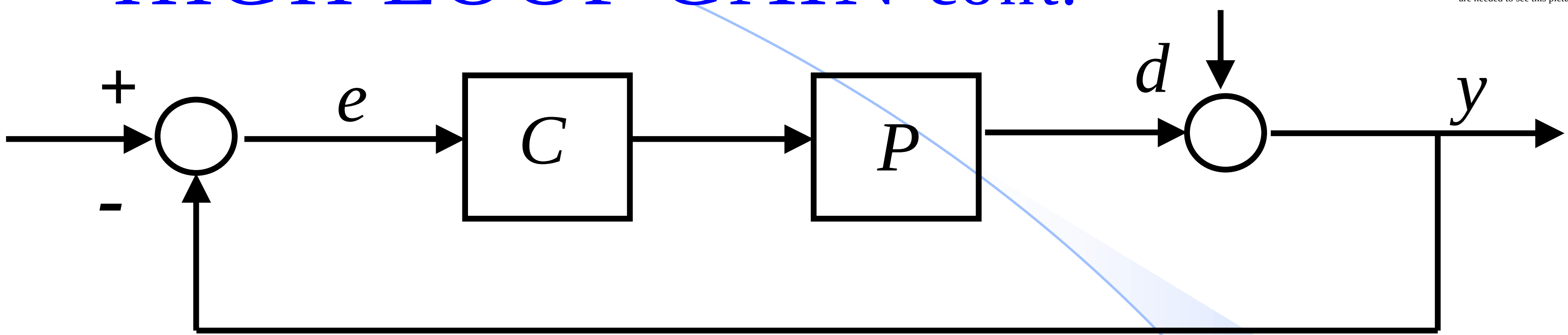
- Loop gain is the amplification between *e* and *y*

- High loop gain means good tracking of *r* by *y*
  - » if *y* is normal size, and gain is high, then *e* must be small
  - » $e = r - y$

- High loop gain with unhelpful time-shifting at a frequency could produce positive feedback and oscillatory behaviour

HIGH LOOP GAIN cont.

QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.



- *d* is disturbance (wind gust)
- *d* is fed back and compensatory signal may be generated
- *y* is adjusted by $\dfrac{d}{1 + \text{gain}}$, so high gain is good
- similarly, there is compensation for changes in *P* (due to e.g. ageing, environmental change etc): 10% change in *P* may produce 1% change only in *y*

OVERALL DESIGN FLAVOUR AND SHORTCOMINGS

QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

- Rule of thumb oriented
- Multivariable impossible
- Time-varying impossible
- Graphically based
- Very limited numbers of design parameters
- Optimization not usually possible
- Stochastic/Noise Problems not tackled

SOME OTHER DEVELOPMENTS IN PRE-COMPUTER PERIOD

QuickTime™ and a Photo - JPEG decompressor are needed to see this picture.

- Relay control

  (German V weapons)

- Wiener filtering

  (for directing anti-aircraft guns)

- Start of sampled data or computer control

  (but no textbooks)

QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

- PRE-SCIENTIFIC AUTOMATION AND CONTROL
  (17th - 19th Centuries)

- THE SCIENTIFIC PRE-COMPUTER PERIOD
  (1900 - 1955)

- SOME MAJOR DEVELOPMENTS
  (1955 - 2000)
  - » LQG Design
  - » The Kalman Filter
  - » Adaptive Control

- WHAT OF THE FUTURE?

LINEAR-QUADRATIC GAUSSIAN DESIGN

QuickTime™ and a Photo - JPEG decompressor are needed to see this picture.

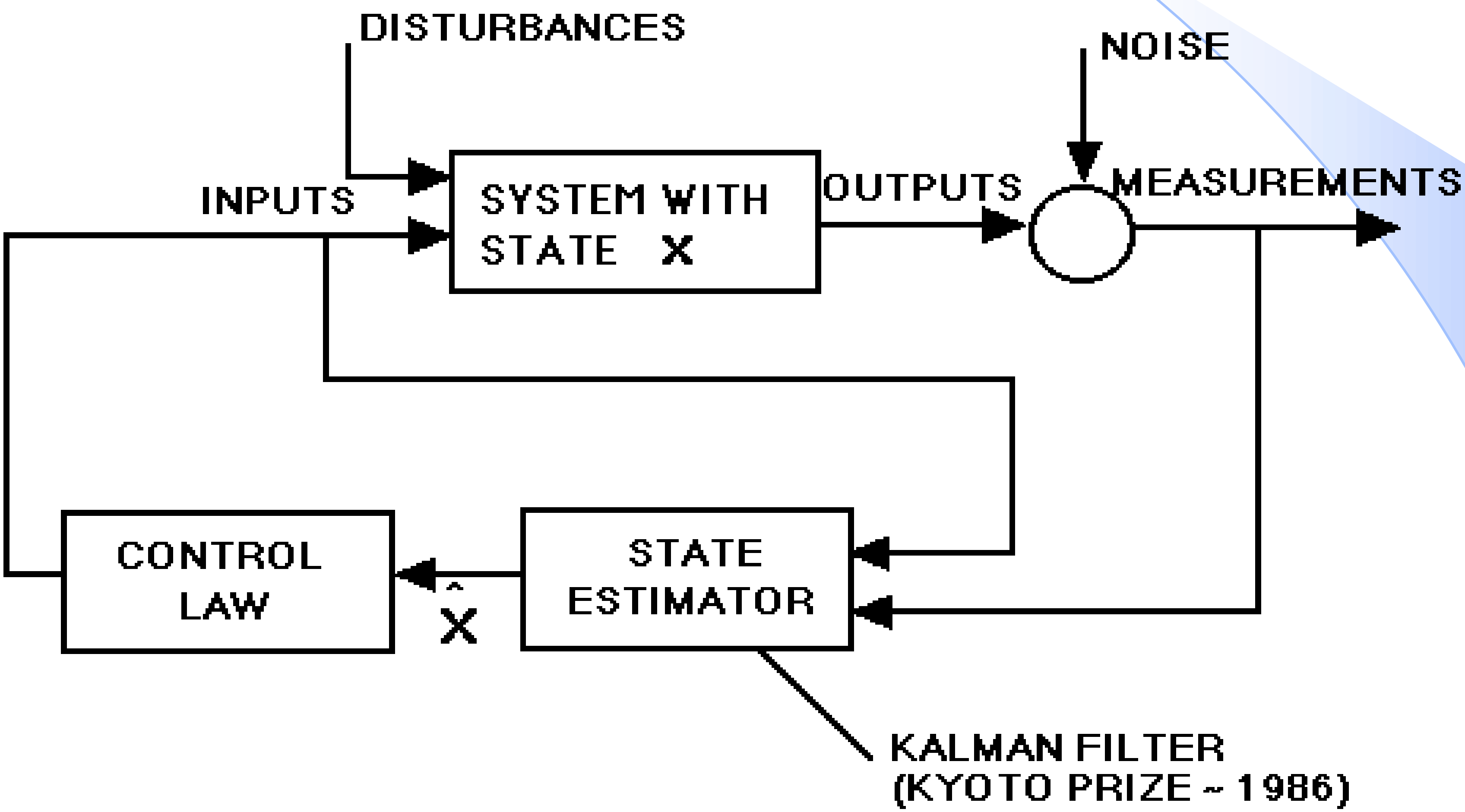
- Allows multivariable
  high dimension
  stochastic or random signals

- Pitch control system for commercial aeroplane
  2 inputs, flaps, ailerons
  2 outputs, attitude, angular velocity
  40-50 states
  stochastic disturbances : wind

- Key theoretical idea is as follows

LINEAR-QUADRATIC GAUSSIAN DESIGN cont.

QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.



SOME KEY ISSUES

QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

- How to set software knobs (design parameters) to achieve specifications (on stress levels etc)
- How to allow for fact that at different heights and speeds the aeroplane model changes
- How to get a simple controller, even though the aeroplane model is complicated

SOME KEY ISSUES cont.

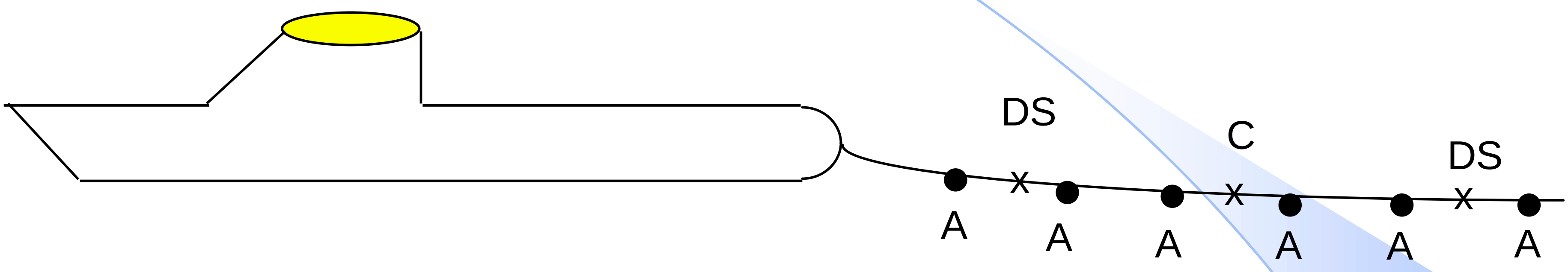
QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

- Boeing experience
  - » Non LQG designs by trial and error gave simple controller with 200 person years effort
  - » LQG designs gave complicated controller

- ANU provided design methodology for simplifying complicated controller, now implemented in commercial software

THE KALMAN FILTER AND AN APPLICATIONS PROBLEM

QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.



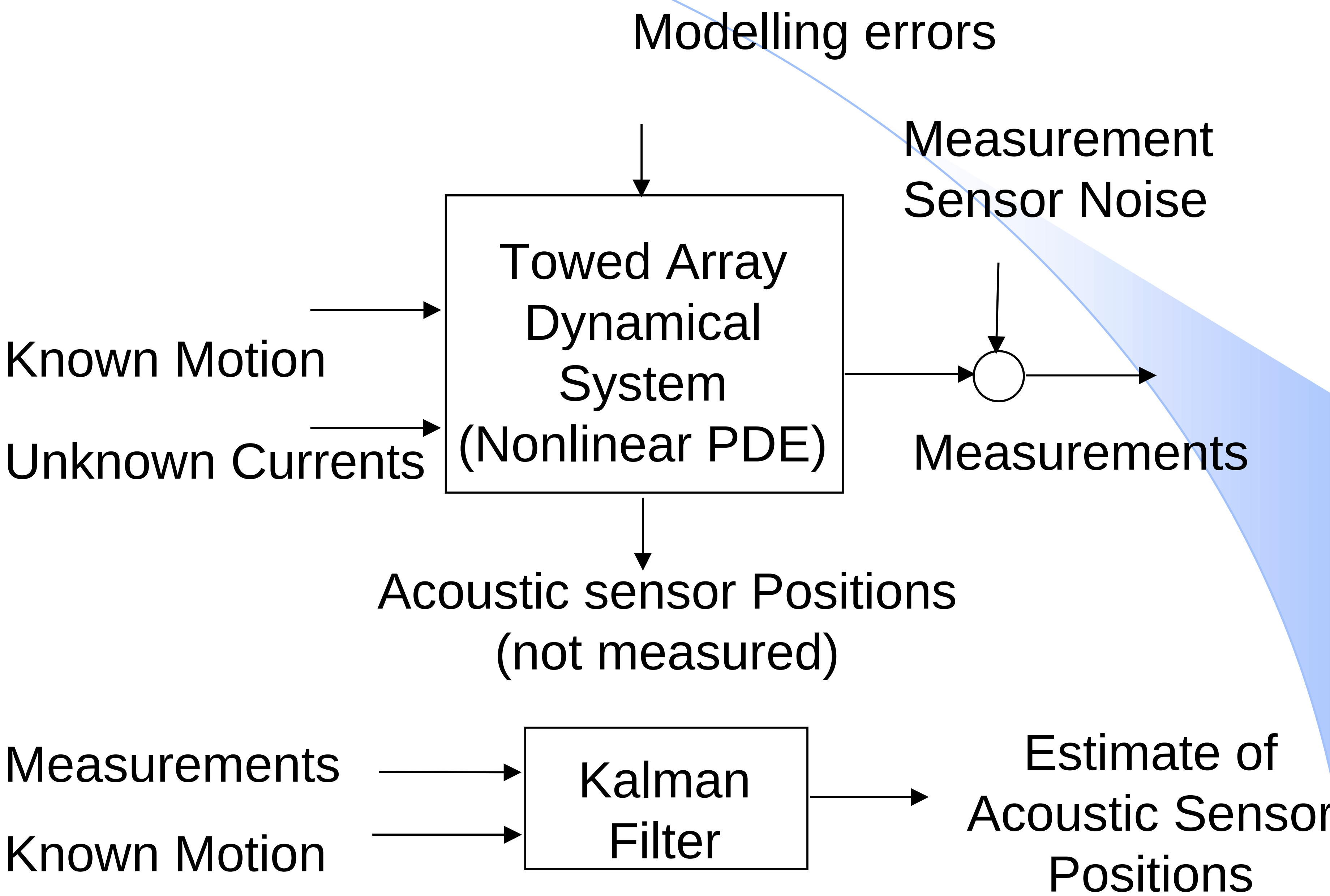
- Submarine trails a towed array.
- A = acoustic sensor is to listen for other vessels.
- Shape of array must be known to use information from A
- DS and C denote depth sensor and compass.

THE KALMAN FILTER AND AN APPLICATIONS PROBLEM cont.

QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

- Motion of submarine + equations for towed cable give an estimate of shape, but
  - there is modelling error
  - there are currents.

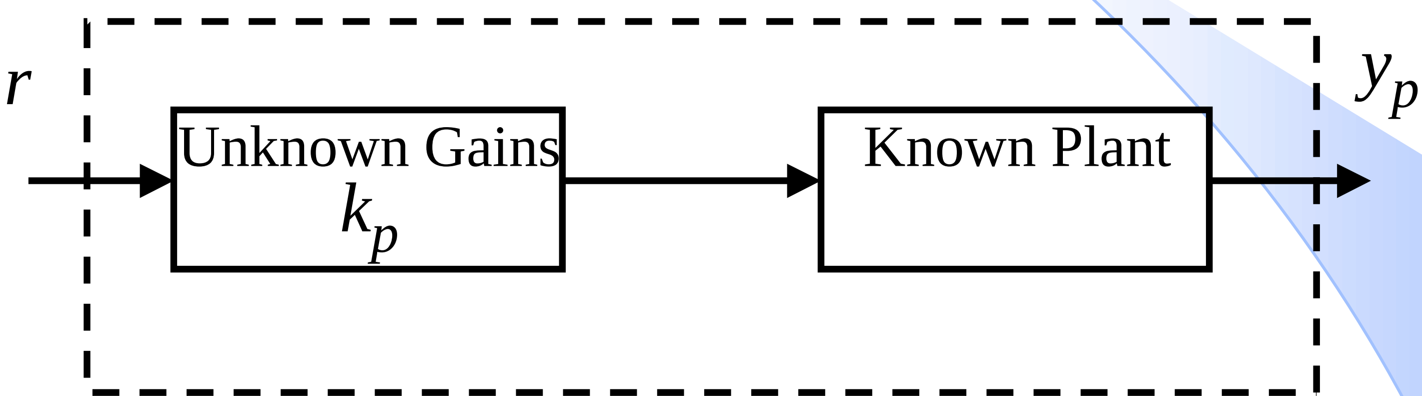
- Depth sensors, DS, and Compasses, C, provide (noisy) measurement information.


Modelling errors
Measurement
Sensor Noise
Towed Array
Dynamical
System
(Nonlinear PDE)
Known Motion
Unknown Currents
Measurements
Acoustic sensor Positions
(not measured)
Measurements
Known Motion
Kalman
Filter
Estimate of
Acoustic Sensor
Positions

ADAPTIVE CONTROL

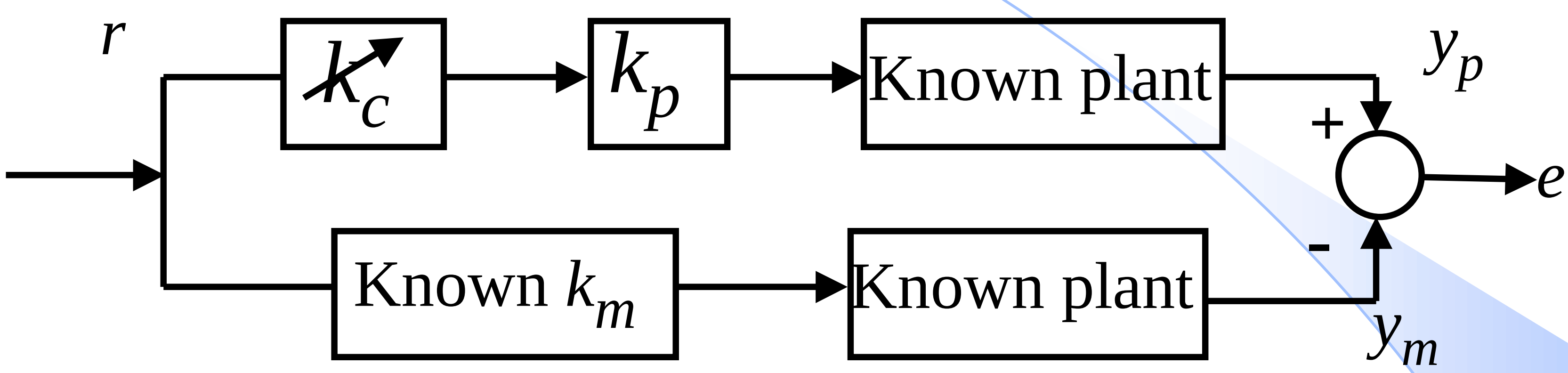
QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

- An original question of adaptive control (fighter aircraft application)



- How can we design a controller that learns k_p (and maybe tracks it)

ADAPTIVE CONTROL cont.



- Idea:

  if $y_p > y_m > 0$, decrease k_c

  if $0 > y_p > y_m$, increase k_c etc

- $\dot{k}_c = -g\,[y_p - y_m]\,y_m$ ($\dot{k}_c$ = *change rate for* k_c)

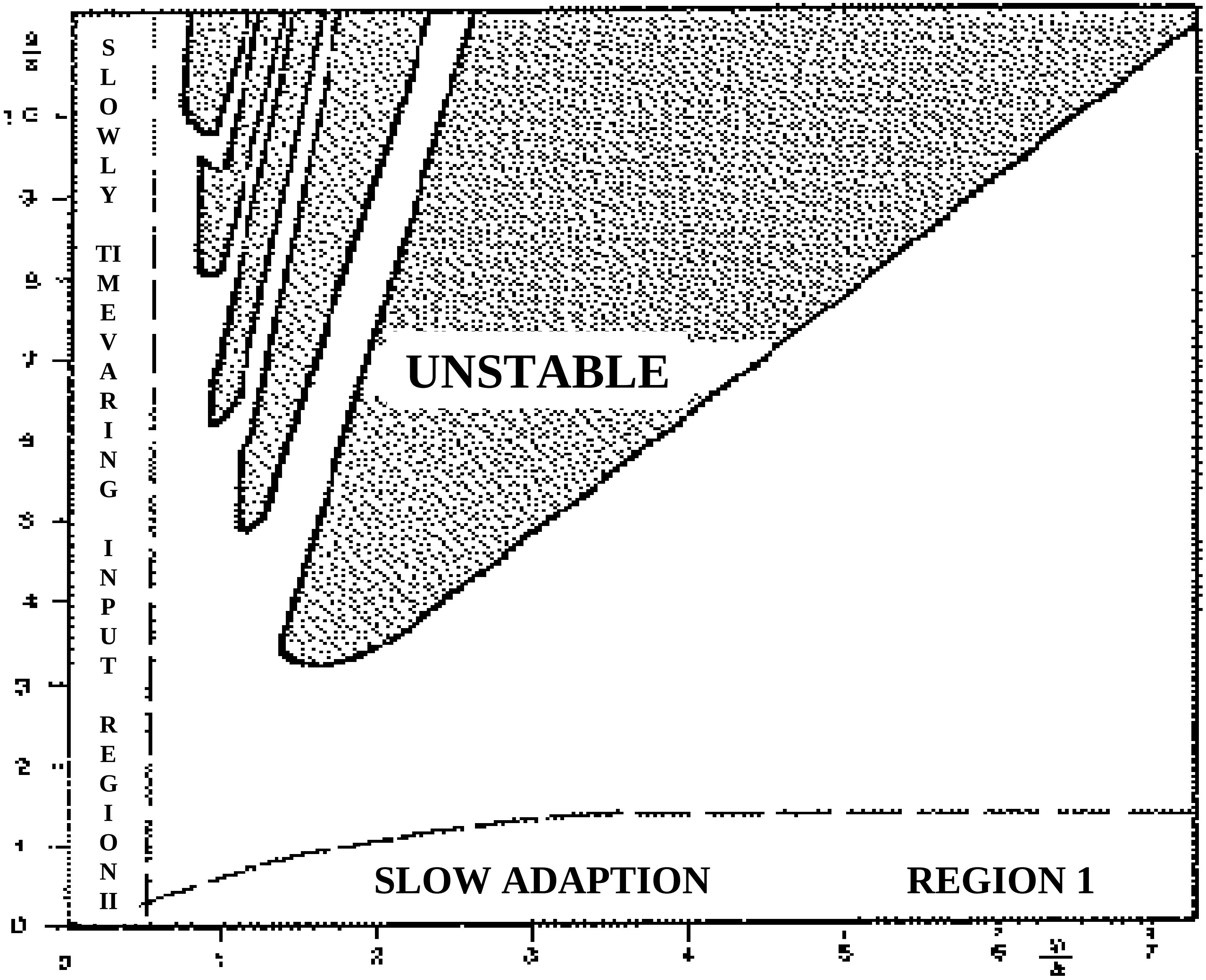
  g is "adaptive gain" (MIT Rule)

- Hope: k_c changes to drive *e* to zero

- Unable to explain performance

QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

GAIN



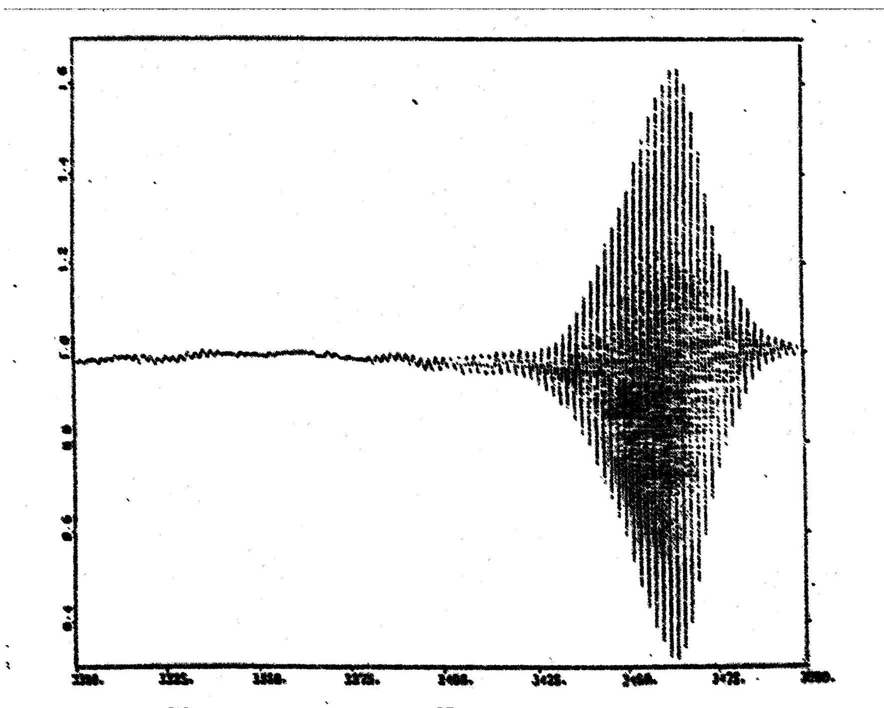
EXCITATION FREQUENCY

QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

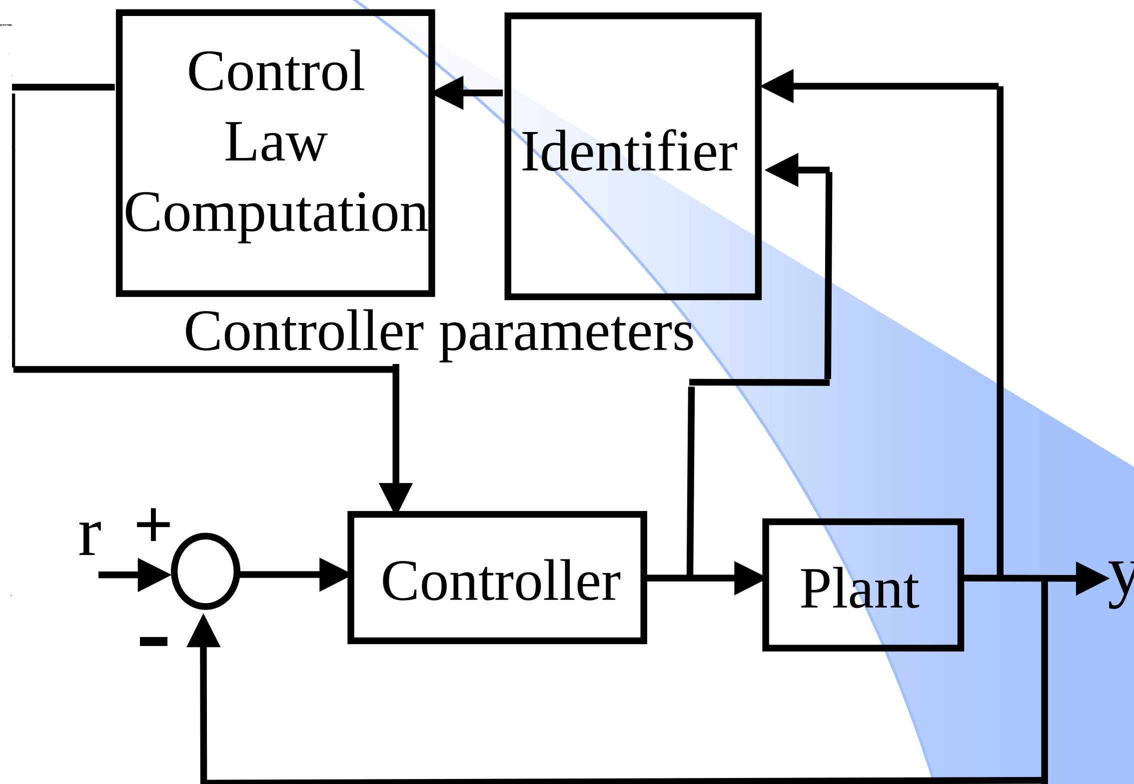
- Unable to predict performance in similar but different, sometimes more sophisticated situations, i.e. no theory
- No use of adaptive control for 15 - 20 years
- New approaches to adaptive control were needed
- Theory for MIT Rule first available 1986
  - » Enabled consideration of many other adaptive schemes
- Adaptive schemes strive for AUTOMATIC TUNING of the controller in response to (typically environment-induced) changes to the plant, or learning the plant in the first place

ADAPTIVE CONTROL AND THE BURSTING PHENOMENON

OUTPUT



TIME



- How can one explain bursting phenomenon (and avoid them)?

QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

- The task of the identifier is to figure out a number of parameters of the plant
- If r is constant, and the plant input and output are constant, one can only reliably figure out one parameter, namely the gain to constant level signal
- The output of the identifier thus has one legitimate parameter and many spurious values that will drift
- The control law will change and may produce a destabilizing controller

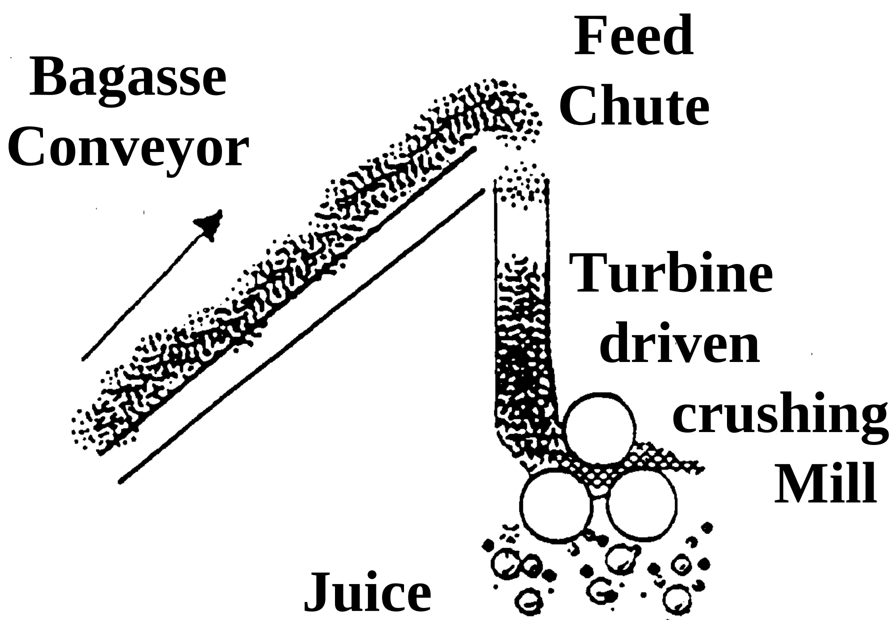
QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

- The plant is then more richly excited, the identifier can learn more legitimate parameters and correct the control law

- Avoid bursting by switching off adaptation when excitation is not rich

SUGAR MILL

QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.



SUGAR MILL CONTROL EXAMPLE

- **Controlled signals**
  - **: feedchute height**
  - **: turbine torque**
- **Controlling signals**
  - **: chute aperture (feedrate to crushers)**
  - **: turbine governor speed**

- **Better extraction comes from greater torque**
- **Sharp variations in feedstock occur**
- **Control via adaptive control for one loop, fixed control for second loop (CSR & ANU)**

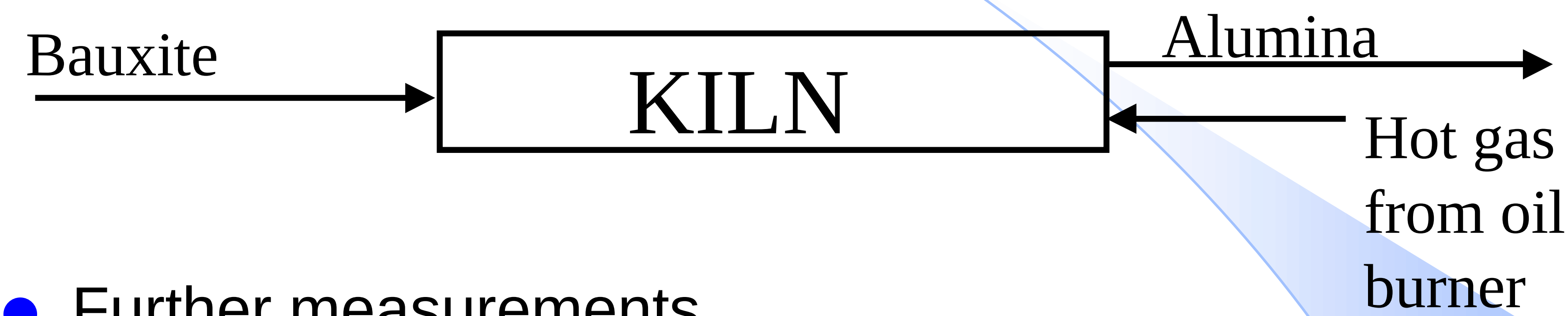
ALUMINA CALCINER

QuickTime™ and a Photo - JPEG decompressor are needed to see this picture.

- Controlled Variables
  - » Discharge alumina temperature (product quality)
  - » Temperature fluctuation (maintenance cost)
  - » Energy Consumption
- Control Variables
  - » Bauxite feedrate
  - » Oil mass feedrate
  - » Air mass feedrate

ALUMINA CALCINER cont.

QuickTime™ and a Photo - JPEG decompressor are needed to see this picture.



- Further measurements
  - » Cold end temperature
  - » CO, O_2
- Little chance of modelling mathematically in advance
- Adaptive control works by learning parameters in a model, given a structure

QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

- PRE-SCIENTIFIC AUTOMATION AND CONTROL
- THE SCIENTIFIC PRE-COMPUTER PERIOD
  (1900 - 1955)
- SOME MAJOR DEVELOPMENTS
  (1955 - 2000)
- WHAT OF THE FUTURE?

WHAT OF THE FUTURE?

QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

- Applications and Challenges:

  Environment

  Automobiles

  Robots

  Discrete-Event Systems

  Systems of Systems

  Hierarchical Systems

A ROBOT CHALLENGE

QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

- Rent a robot to help you move your grand piano from the ground floor to the next floor

- What do we need?
  - » Very sophisticated sensors (vision, pressure)
  - » “Intelligence” for understanding commands, path planning, testing how heavy the piano is, putting the piano down temporarily to change lifting point etc.
  - » Advanced mechanical engineering
  - » Assurance of safety
  - » Implementation of a hierarchical/cooperative control concept

DISCRETE EVENT SYSTEMS

QuickTime™ and a Photo - JPEG decompressor are needed to see this picture.

- A manufacturing production line is an example of a discrete event system:
  - » a part arrives
  - » a machining step is completed
  - » a machine goes out of service expectedly or unexpectedly

- Control Strategies
  - » cope with problems
  - » allow for maintenance
  - » may allow for multiple parts
  - » give guidance about investment in the line

DISCRETE EVENT SYSTEMS cont.

An airport is an example of a system with:

- discrete events (landing, take off, passenger arrival/departure, freeing of a gate, repair of a runway)
- cooperative and hierarchical control
- deterministic and random phenomenon (scheduled arrivals, weather-induced delays, crashes, Olympic Games disturbances)
- multiple optimization criteria (customers, airline companies, nearby homeowners)
- the need to adapt (in response to long term traffic changes/technology changes)

SYSTEMS OF SYSTEMS

- Providing a control system for a locomotive is easy. The manufacturer provides it.
- Imagine a 2km length ore train with 4 locomotives, travelling on a nonflat track
- How does one control that?

HIERARCHICAL SYSTEM

- How should a company be organised?
- There are layers in a company, for example:

  The shopfloor person,
  thinking about the next hour
  The shift foreman,
  thinking about the day
  The production engineer,
  thinking about the month
  The plant manager,
  thinking about the year
  The CEO,
  thinking about the next 5 years

HIERARCHICAL SYSTEM cont.

QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

- By and large, each level reports upwards, issues instructions downwards, and cooperates with peers at the same level
- Information gets summarized as it goes up, detail gets added to instructions as they go down
- Performance objectives are clear near the bottom, less clear up the top. Strategies (control laws) may be very unclear up the top

HIERARCHICAL SYSTEM cont.

- Can one give a theory to answer questions like:
  - How many layers are optimum ?
  - How should upwards flowing information be compressed ?
  - How should one build in adaptivity ?

- There are major associated IT problems for example:
  - how can one capture the tacit knowledge of employees, so that it remains available when they leave?

THANKS

- My career as a researcher has been immeasureably enriched by the many individuals with whom I have interacted, especially in collaborative research projects
- I would particularly like to thank the Hong Kong Polytechnic University for honoring me with this invitation
- Lastly, I would like to thank you for your attention