Intelligence Through Multiple Models, Switching and Tuning

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Overview

- Biological Systems
- Engineering Systems: Principal Difficulties
- Intelligence Through Multiple Models
- Applications
- Conclusions and Future work

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Biological Systems

The Brain

" … in contrast to man-made computers that are highly constrained, precisely laid out, not very fault-tolerant, largely serial, centralized, deterministic and minimally adaptive, the brain is massively parallel, densely connected with leaky transmission paths, fault-tolerant, self-repairing, adaptive, noisy and stochastic, and performs the acts of perception, cognition and decision making with tremendous efficiency, even while using natural processing elements which are orders of magnitude slower than current computer processing elements."

L.Kleinrock (1985)

Biological Examples

- Flocks and Schools - (Decentralized System)
- Chimpanzees and Bananas - (Improvisation)
- Honey bees and flowers - (Pattern Recognition and Decision)
- Vervet monkeys and alarm calls - (Multiple Models)
- Pride of lions hunting - (Game Theory)
- Ducks landing in high wind - (Robust Adaptive System)
- Ant colonies - (Complex Tasks)

Chimpanzees and Bananas

Chimpanzees with boxes to stand on, sticks that fit together, and bananas out of reach, quickly learn to push the box under the bananas, put the sticks together, stand on the box, and knock the bananas down.

This is an intelligent system in the truest sense of the word.

Vervet Monkeys

- Emit alarm calls to warn the other monkeys.
- There are eagle calls, leopard calls, baboon calls, and snake calls.
- The calls elicit appropriate responses.

The above corresponds to multiple models and control.

Formation Flying makes Migration Less of a Drag

V - formation: Migrating geese, cranes and ducks.

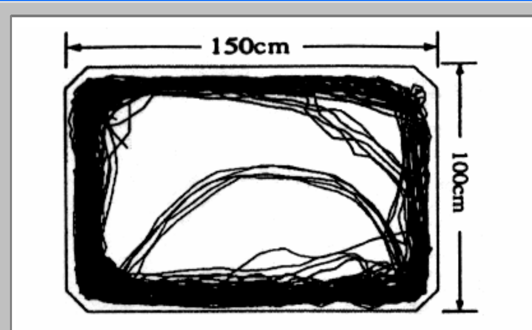
- All birds experience the same amount of benefit.
- 25 birds in formation can fly 70% farther than a single bird.
- Loners pay a price - increased friction.
- Birds won't stand for malingerers.

Adaptability to Environmental Variations

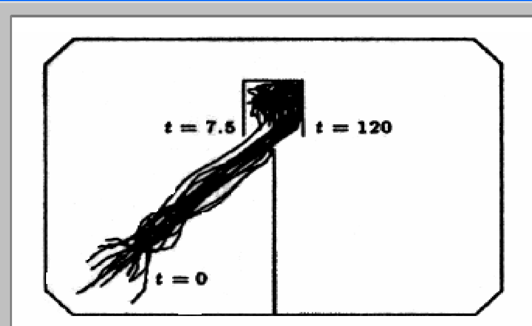
Yajie Tian Nobuo Sannomiya Hiroshi Nakamine

Bitterling

Swimming Trajectory

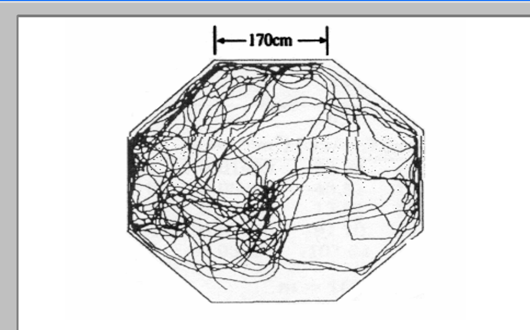


Trajectories of 20 individuals

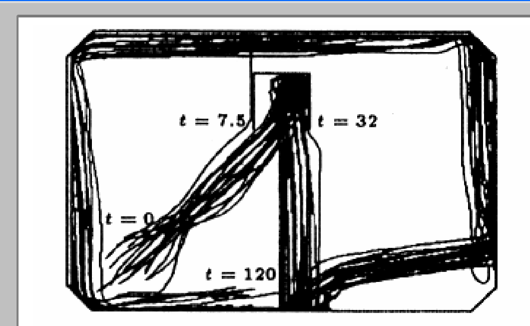


Tilapia

Swimming Trajectory



Trajectories of 20 individuals



"Swarm Intelligence"

Eric Bonabeau, Marco Dorigo, and Guy Théraulaz

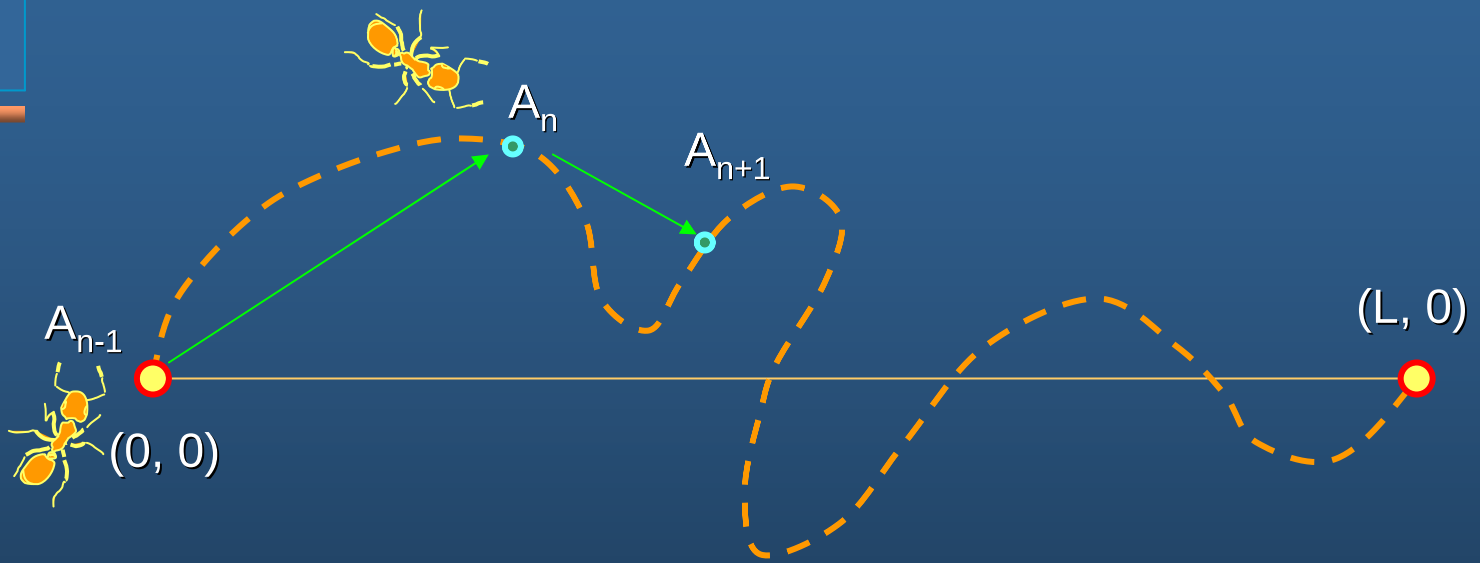
"Insects that live in colonies, ants, bees, wasps and termites, have fascinated naturalists as well as poets for many years"

"What is it that governs here? What is it that issues orders, foresees the future, elaborates plans and preserves equilibrium?"

Maurice Maeterlinck

"Every single insect in a social insect colony seems to have its own agenda and yet an insect colony looks so organized"

Feynman's Question



"One question that I wondered about was why the ant trails look so straight and nice. The ants look as if they know what they are doing, as if they have a good sense of geometry."

Surely You're Joking, Mr Feynman!

Swarm Intelligence: Ants

- Ants, unlike motorists, can avoid traffic jams:

"When the road gets crowded, the garden ant, *Lasius niger*, looks for another route"

Audrey Dussutour, Centre for Research into Animal Cognition, France

- Different ants arrive at different solutions:

"The army ants seemed to be very good at setting up three lanes automatically whereas these black garden ants seem to be capable of selecting an entirely different path"

Nigel Franks, University of Bristol, U.K.

Ants vs. Humans

"If a leafcutter ant was a 1.8 metre tall human, it would run a km in two minutes 20 seconds, and keep up that pace over a whole marathon. Then it would pick up a load weighing 150 kg, and run all the way back at the slightly slower speed of a km every two-and-a-half minutes"

Edward O Wilson, Harvard University, USA.

Ants, creatures with brains each the size of a speck of dust, can move house, measure the floor area of a nest and avoid traffic jams.

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Engineering Systems

Euclid and Ptolemy I

“Is there a shortcut to geometric knowledge?”

Ptolemy I, King of Egypt, to Euclid, his teacher

“Euclid’s answer:

“Sire, there is no royal road to geometry”

There is no easy path to building intelligent systems!

What makes the problem difficult?

- Uncertainty
- Complexity
- Nonlinearity
- Time-variations

Why Uncertainty?

1. Real physical system: the one ‘out there’.
2. Ideal physical system: decomposing the real physical system into ideal building blocks.
3. Ideal mathematical model: applying mathematical laws to the ideal physical system.
4. Simplifying assumptions: linearisation; lumping, etc.

Uncertainty

Therefore,

- Different models are available.
- No model is a true representation of the system!

Uncertainty: Difference between the model, and the reality it represents.

Ignorance

In addition,

- Incomplete knowledge of the physical system.
- Insufficient knowledge of the environment, and its effect on the physical system.

Ignorance: Adds to the designer's problems!

Coping With Uncertainty

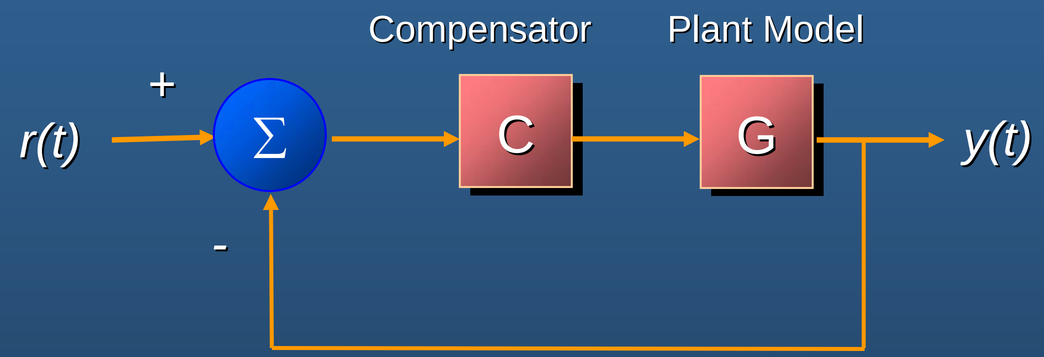
- Live with it: *Robust System*
- Reduce it: *Adaptive System*

Robust Systems

A system that performs satisfactorily with the design model, and as well as over the uncertainty class is called robust:

Similar behaviour for all models ‘close’ to the design model.

Robustness: A Naïve Example



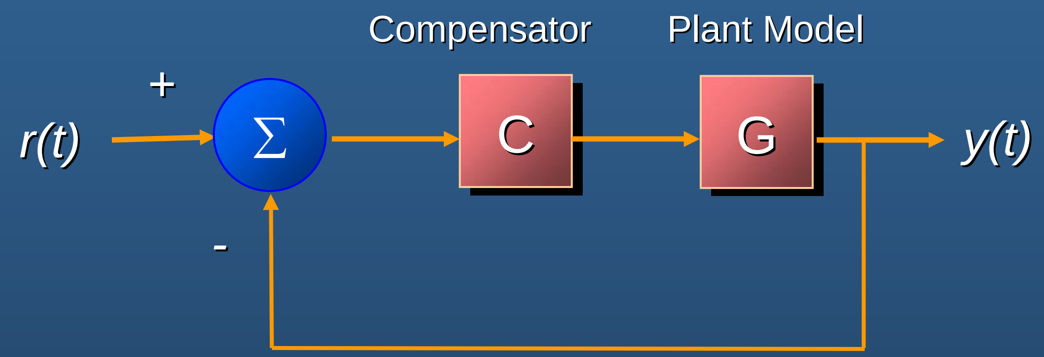
$$G(s) = \frac{1}{s-2}$$

$$C(s) = \frac{s-2}{s+2}$$

$$T(s) = \frac{1}{s+3}$$

- System is stable
- Performance is satisfactory

Robustness: A Naïve Example (Contd.)



$$G_{\varepsilon}(s) = \frac{1}{s-2.01}$$

$$C(s) = \frac{s-2}{s+2}$$

$$T_{\varepsilon}(s) = \frac{s-2.01}{(s+2.9998)(s-2.008)}$$

- System is unstable

Design is not robust!

Earliest Attempt to Introduce Robustness

" .. by building an amplifier whose gain is deliberately made say 40 decibels higher than necessary (10,000 fold excess on energy basis) and then feeding the output back on the input in such a way as to throw away excess gain, it has been found possible to effect extraordinarily improvement in constancy of amplification and freedom from nonlinearity."

H. S. Black, 1920s

Complex Control Systems

In more complex problems such as

- air traffic control, or
- control of multiple autonomous vehicles,

  - routes and missions have to be planned

  - guidance and control laws have to be developed

taking into account

maneuverability, endurance, survivability, collision avoidance, situation awareness, and contingency planning.

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Intelligent Systems

Words and Definitions

- The great efficiency of control strategies in the biological world has led to the adoption of a variety of terms such as

adaptation, learning, pattern recognition,
and artificial intelligence

- Intelligent control represents the latest evolution in this trend.
- All the above terms are imprecise. However, they are useful in that they help us to communicate.

Adaptation

- Problems of adaptation occur in many diverse fields:

  Evolution - Ecology - Psychology - Economics - Control - Artificial Intelligence - Computational Mathematics - Inference.

- Adaptation arises in various guises but the fundamental questions are the same.

- Optimization in real time in the presence of great uncertainty, complexity, nonlinearity, and time variations.

Intelligent Systems

- Intelligence is what you use when you do not know what to do.

Jean Piaget

- Intelligent systems improvise.
- They create a wide repertoire of behaviours for different situations.
- They combine existing programs to cause novel behaviour.
- They evolve on the fly.

Intelligence Through Multiple Models

- Intelligently designed interconnections of information processing capabilities.
- Intelligent control implies the controller's ability to decide to which specific problem has arisen and service it using appropriate strategies.
- Multiple Models and controllers may have to be used to characterize "a wide repertoire of behaviours."
- Design may involve the synthesis of concepts from optimal control, adaptive control, AI, and neural networks.

Philosophy

- As in biological systems, build up a repertoire of solutions.
- Switch to the “best” solution at any instant.
- Adapt from that point.
- Show that the system is stable.

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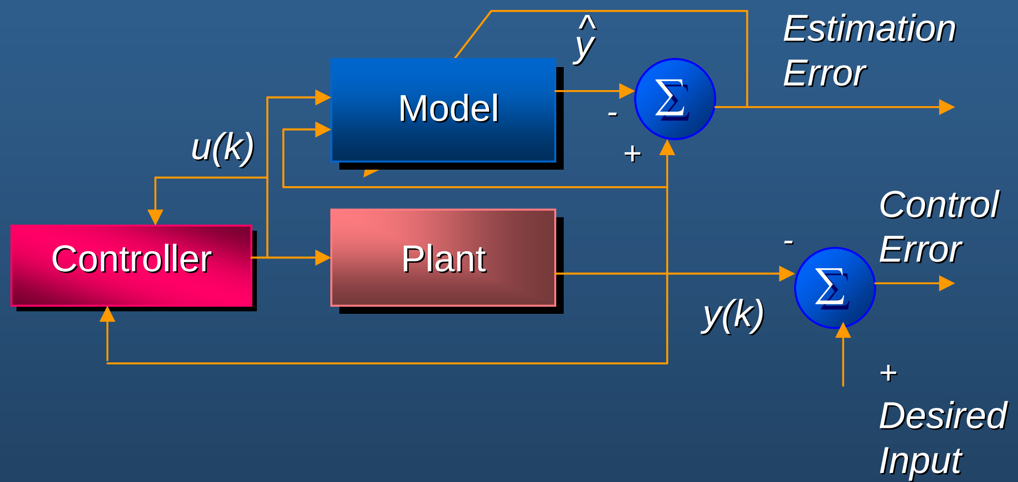
Intelligence Through Multiple Models

Adaptive Control - One Model (1970-1990)

AtIS-07

- Continuous time:
  K.S. Narendra et al.
- Discrete time:
  G.C. Goodwin et al.
  S. Morse



- Estimate plant parameters on-line
- Use the estimates to determine the control input (certainty equivalence)
- Prove stability

Assumption: Plant parameters constant but unknown

Performance

Adaptive Control implies

- Incremental changes in model and controller parameters.
- Model is chosen for mathematical tractability (i.e. stability).

- Satisfactory if initial parametric errors are small.
- Large transients with large parameter variations.

Models

- Linear and Nonlinear.
- Static and Dynamic.
- Continuous-time and discrete-time.
- Deterministic and Stochastic.
- Fixed and Adaptive.
- Special purpose models
    - Sensor failure, Actuator failure

Multiple Models

- Every model of a system is based on some simplifying assumptions.
- More than one model may be useful for understanding different aspects of the same phenomenon.
- The designer chooses the models based on both theoretical and practical considerations.

Need for Multiple Models

- Large and rapid changes in plant dynamics
  - Faults, subsystem failures
- Large changes in disturbances
- Sensor and actuator failures

- Computational resources and prior information about plant dynamics are available to compute solutions off-line.

Other Reasons for Using Multiple Models

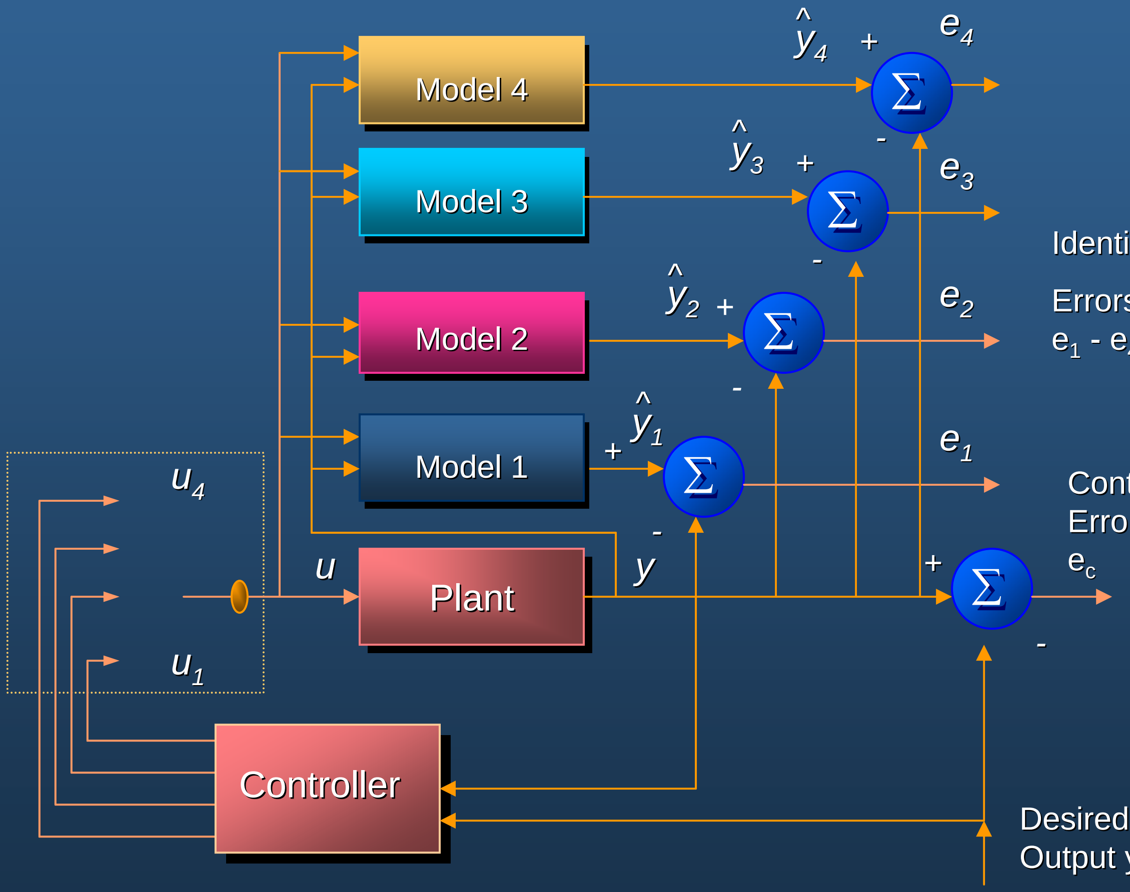
- Combining the advantages of different models
- Robustness
- To cope with varying delays

Creating a wide repertoire of behaviours for different situations

Intelligent Control Using Multiple Models

AtIS-07

- K.S. Narendra and J. Balakrishnan
    - 1992
    - 1997



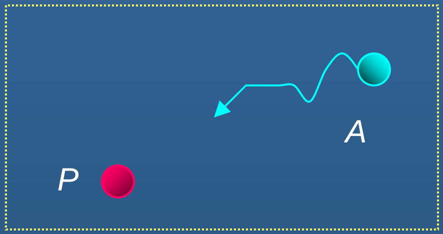
Control Structure

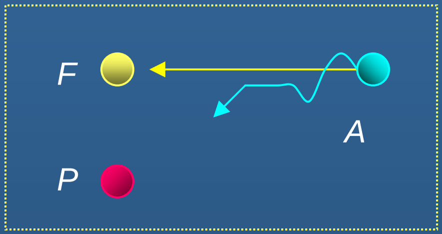
Problems in Adaptive Control Using Multiple Models and Switching

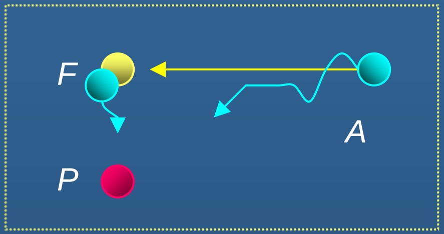
- How are the models chosen?
- When should we switch and to which model?
- Does switching stop? If so, when?
- Fast switching in rapidly varying environments.
- Can models be unstable?
- Stability questions - deterministic and stochastic cases.
  - linear and nonlinear
  - changes in performance index

Rationale for Switching and Tuning

AtIS-07





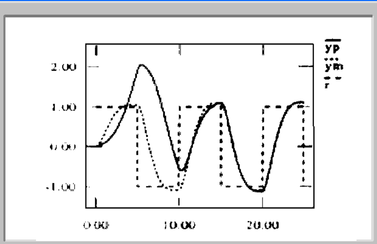


A: Adaptive Model

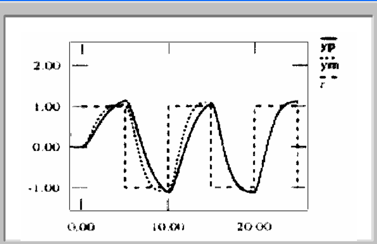
F: Fixed Model

P: Plant

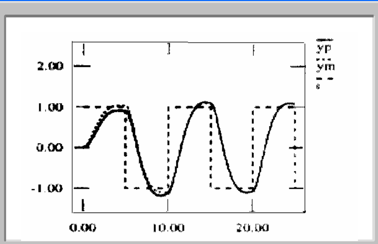
Adaptive Model only



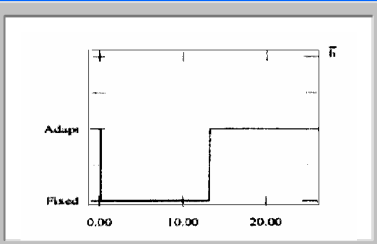
Additional Fixed Model



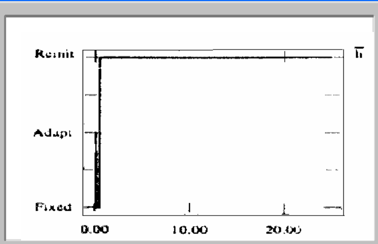
Add. Re-initialized Adap. Model



Switching Add Fixed Model



Switching Re-initialized Model



The Stability Problem

- Deterministic adaptive control.
- Stochastic adaptive control.
- Adaptive control of nonlinear systems.

} Using Multiple Models

- Combining linear and nonlinear models for improved performance.

Summary

Switching between fixed controllers is also adaptive control

- Switching - to come close to the plant (fast adaptation)
- Tuning - to improve performance (slow adaptation)

The MMST methodology extends standard adaptive control.

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Applications

Applications

1. Fault Detection and Control
2. Flexible Transmission System
3. Unmanned Combat Air Vehicles (UCAV)
4. Autonomous Navigation
5. Process Control
6. Intelligent Arc Furnace
7. Steel Rolling Mill
8. Robotics
9. Engine Speed Control.

Comments and Conclusions

1. The multiple models correspond to a finite repertoire of behaviours. The controller has to decide which type of problem has arisen, and service it using the appropriate control strategy.

2. Switching to avoid catastrophic failure - Tuning to improve performance.

3. The stability of deterministic and stochastic switching and tuning systems has been demonstrated. Some results have been extended to special classes of nonlinear systems.

Comments and Conclusions

4. Switching is also adaptive control. Switching and tuning merely extend conventional adaptive control to larger regions in parameter space.

Adaptive control can therefore be applied to rapidly time-varying systems.

5. The methodology can be used in many situations where multiple approaches are available.

Set-membership Identification and Control - Control in the closed loop - Control in communication problems.

In such cases combining tools from different disciplines will be called for (e.g. pattern recognition and control, queuing theory and control, AI and control).