

# Brief Overview of Adaptive and Learning Control

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# Outline

## Introduction

What are Adaptive and Learning Control?  
Background

## Examples

Classical  
Periodic  
Machine Learning

## Conclusion

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# Definition of Adaptive Control

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- ▶ Zames (reported by Dumont&Huzmezan): “A non-adaptive controller is based solely on a-priori information whereas an adaptive controller is based also on a posteriori information”

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- ▶ Unified view: system state and parameters are all just state, anyway
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# But isn't feedback control *a posteriori*?

- ▶ Unified view: system state and parameters are all just state, anyway
- ▶ Stochastic control solves everything
- ▶ Not possible in practice  
→ need approximations and optimizations
- ▶ The terminology and conceptual organization of the field is based on a long history
  - ▶ Analog components, ...
  - ▶ Analytic proofs, ...

# Approximations and optimizations

- ▶ For example,
  - ▶ Fixed-structure controller with parameters, simple laws to alter those parameters
  - ▶ The system is periodic, and works the same every time

## Definition of Adaptive Control 2

- ▶ Zames (reported by Dumont&Huzmezan): “A non-adaptive controller is based solely on a-priori information whereas an adaptive controller is based also on a posteriori information”
- ▶ Sastry&Bodson: “direct aggregation of a (non-adaptive) control methodology with some form of recursive system identification”

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- ▶ Adaptive controller depends on very recent history
  - ▶ No memory
  - ▶ Reacts to current state only
- ▶ Learning controller depends on long-term history
  - ▶ Memory
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- ▶ Again, from the grand unified stochastic control perspective, these are the same

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- ▶ Direct = adapt or identify controller parameters directly
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## Direct — Indirect

- ▶ Direct = adapt or identify controller parameters directly
- ▶ Indirect = adapt model of system, calculate controller parameters from model
- ▶ Even here, the only difference is conceptual

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# Motivating example

- ▶ Two-armed bandit
- ▶ System has two actions
- ▶ Each action gives a reward from an unknown but constant distribution
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# Motivating example

- ▶ Two-armed bandit
- ▶ System has two actions
- ▶ Each action gives a reward from an unknown but constant distribution
- ▶ How to maximize the wins?
- ▶ Must take into account information from the system when making the decision, but also the uncertainty of the information, and optimize both.

# Mathematical Methods

- ▶ Laplace transform
  - ▶ Used all through control theory
- ▶ Lyapunov functions
  - ▶ Can show convergence of certain controllers, *provided assumptions hold*

# History

- ▶ 50s: Initial algorithms
- ▶ 60s: Dynamic Programming and Dual Control — intractable
- ▶ 70s and 80s: Convergence proofs
- ▶ 80s-90s: Reinforcement learning and neural methods

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# Algorithms

- ▶ Classical Adaptive
  - ▶ Gain Scheduling
  - ▶ MRAC (Model Reference Adaptive Control)
  - ▶ Self-tuning regulator
  - ▶ SOAS (Self-Oscillating Adaptive Systems)
- ▶ Periodic Adaptive / Learning
  - ▶ ILC (Iterative Learning Control)
  - ▶ RC (Repetitive Control)
- ▶ Machine Learning
  - ▶ Reinforcement Learning

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# Gain Scheduling

- ▶ Determine controller parameters directly from measurements “unrelated” to the process
- ▶ Example: use measured air pressure and velocity to determine feedback gain in an aeroplane pitch controller — otherwise, trouble
- ▶ Usually linear interpolation between controllers designed for particular parameter values
- ▶ Works well in certain problems

# Gain Scheduling

- ▶ Determine controller parameters directly from measurements “unrelated” to the process
- ▶ Example: use measured air pressure and velocity to determine feedback gain in an aeroplane pitch controller — otherwise, trouble
- ▶ Usually linear interpolation between controllers designed for particular parameter values
- ▶ Works well in certain problems
- ▶ Difficulties:
  - ▶ Need to find good variables to measure
  - ▶ May need lots of controllers to interpolate between

# MRAC (Model Reference Adaptive Control)

- ▶ Drive difference between plant and reference model to zero by adapting controller parameters directly
- ▶ Ad hoc rules: e.g., high-gain servo
- ▶ MIT rule: gradient descent + assume unknown parameters are the estimated values for calculating gradient
  - ▶ Can be unstable
- ▶ Many variants

# Self Tuning Regulators

- ▶ Use parameterized control design equations for a plant
- ▶ Identify parameters on-line
- ▶ Apply controller for those parameters — “Certainty Equivalence”
- ▶ Harder to analyze
  - ▶ Design equations usually nonlinear

# SOAS - Self-Oscillating Adaptive Systems

- ▶ Use relay to discretize control signal
- ▶ Use dithered error to control relay
- ▶ Adapt gain of relay based on limit cycle amplitude
- ▶ Instance of MRAS, with constant excitation designed into the system

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# Periodic systems

- ▶ Premise: fixed operation cycle
  - ▶ Robot arm doing repetitive operation
  - ▶ Adjusting voltage to particle accelerator magnet
- ▶ Premise: Error has periodic part

# ILC and RC

- ▶ ILC = Iterative Learning Control, RC = Repetitive Control
- ▶ Eliminate periodic error
- ▶ Record error as a function of time, use on the subsequent cycles to improve control
  - ▶ Heuristically: “At 2.54 seconds, the robot arm usually goes too far left, so use force to the right at that point”
- ▶ Works well with non-linear and difficult-to-model systems
- ▶ Stability sometimes difficult to obtain, need various filters
- ▶ Difference between schemes:
  - ▶ ILC assumes known initial state for each period
  - ▶ RC lets end of previous period affect start of next (transients)

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# Reinforcement Learning

- ▶ System = states, actions
- ▶ Step = act, get reward
- ▶ Goal: maximize reward over time
  - ▶ Decide what to do (policy)
  - ▶ Update policy over time to reflect reward obtained (learning rule), directly or indirectly
- ▶ Main variability
  - ▶ Policy (e.g.,  $\alpha$ -greedy)
  - ▶ Learning method (e.g., Q-learning:  $Q : \text{states} \times \text{actions} \rightarrow R$ )
  - ▶ Function approximation and generalization
    - ▶ Convergence guaranteed only if when there is no extrapolation (details in books)

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# Conclusion

- ▶ Control theory: roots in era of real, analog components
- ▶ On an abstract enough level, it is all just approximations to stochastic control
- ▶ Big changes from neural computation: nonlinear function approximation
- ▶ Methods are difficult to compare since the range of systems to be controlled is huge
- ▶ In the industry, the simplest system that works is good

# Issues with Adaptive Control

- ▶ Unmodeled dynamics cause bad behaviour
- ▶ If a controller regulates well, knowledge of plant's behaviour decays
  - ▶ Need constant or intermittent excitation to know system behaviour
  - ▶ Stochastic Control actually does generate excitations

## Methods not discussed here

- ▶ Neurofuzzy control
  - ▶ Adapt “rules-of-thumb” with data
- ▶ Neural augmentation of classical control methods
  - ▶ Adapting feedforward control
  - ▶ Treating nonlinearities in some area of the control problem using backpropagation neural networks
- ▶ Countless others — the literature is huge

# Hidden Bonus: Model-Predictive Control (MPC)

- ▶ Popular practical control method
- ▶ Original motivation: constraints
- ▶ Uses explicit model
- ▶ Explicitly optimizes control several time steps forwards (sliding horizon)
- ▶ Computationally intensive
  - ▶ Enabled by digital computers