

Natural Computation and Behavioral Robotics

Elements of Adaptive Automatic Control

Overview

- What is Signal Processing ?
- What is Automatic Control ?
- Auto-Regressing Moving-Average models
- Open-Loop and Closed-Loop control
- What is Adaptive Automatic Control ?
- Feedback and Feed-forward Regulators
- Adaptive Control and A.I.

Control and Systems Design

- A system is typically described as a “black box”, i.e. not revealing its internal structure and functionality.
- The behavior of a “black box” module can be studied by systematic correlative measurements between the input and the produced output.
- The analysis can be realized in the time-domain or the frequency-domain, according to each problem.



Control and Systems Design

Basic procedure:

1. Create a simple input pattern, e.g. a very short “pulse” signal or a “stepping-function” signal.
2. Measure the produced output from the system module, i.e. the “Black Box”
3. Approximate the correlative measurements of input-output profiles by an appropriate model.
4. Use the produced model as a “template” to generate and predict the behavior of the “Black Box” for any given input.

Control and Systems Design

- Time-Domain Analysis: The exact sequence of the input values is correlated with the exact sequence of the output values.
- Frequency-Domain Analysis: The sequences of the input and output values are translated into a frequency profile (input spectrum) and a frequency response (output spectrum) accordingly, and the system is analyzed in terms of frequency elements.
- Other: Instead of the standard frequency analysis (Fourier), more generalized transformations can be applied to the input and the output signals (e.g. Wavelets).

Signal Processing – ARMA

Typical model for ARMA(N,M):

$$\sum_{k=0}^N a_k y(n-k) = \sum_{r=0}^M b_r x(n-r) \Leftrightarrow$$

$$y(n) = \frac{1}{a_0} \left(\sum_{r=0}^M b_r x(n-r) - \sum_{k=1}^N a_k y(n-k) \right)$$

“**AR(N)**” : Auto-Regressive, i.e. uses N previous outputs $y(.)$

“**MA(M)**” : Moving-Average, i.e. uses M previous inputs $x(.)$

“**ARMA(N,M)**” : combines an AR(N) and a MA(M) together

Signal Processing – ARMA

- ARMA(N,M) models are very generic in form, they can model any system that uses N previous inputs and/or its own M previous outputs to produce the next output.
- All standard ARMA models are **linear**, i.e. they include input and output terms in the **1st order**.
- They are also used as the base model for frequency-based analysis and design of control modules (digital filters, controllers, etc.)

Automatic Control

Basic approach:

- **Filtering Problem:** Create an approximation model for a “Black Box” and use it to predict its behavior for any input.
- **Control Problem:** The “Black Box” model can be used in reverse mode, i.e. to calculate the appropriate input in order to produce a desired output.

Automatic Control

- In the **Control Problem**, the “output” can be the result of a machine or equipment in a physical process, while the “input” is the appropriate command to produce the desired functionality.
- **Example:** In an **Automatic Pilot Module**, the “output” is the aircraft’s attitude (position, speed, etc), while the “input” is the control commands that a human pilot should give through the cockpit, in order to produce the desired “result” (e.g. land the plane).

Open-Loop and Closed-Loop

- Open-Loop Control: A specific “reference point” is used to calculate the required action (correction step) based only on this fixed value and the current **input**.
- Closed-Loop Control: A specific “optimal condition” is used to define the system’s “optimal” behavior and the required action (correction step) is based on the current **input** **AND** the system’s own produced **output** in the previous steps.

Note: In Open-Loop control the correction is calculated upon the input and the “Black-Box” model only, while in the Closed-Loop the actual output of the “Black-Box” model is fed-back as an additional correction factor (“feedback”).

Adaptive Automatic Control

- A typical automatic control model is able to produce the correct “result”, **as long as the system is stationary**, i.e. as long as the conditions and the environment stays the same (→ the design is valid)
- Instead, if the environment changes then the model has to be **re-designed** in order to conform to the new specifications of the “Black Box”.
- If this is too difficult or too costly to do, or if such changes are very frequent, the system has to be able to do it by itself (**self-adjustment**).

Adaptive Systems – Taxonomy

Class-I: “Feedback Regulators with No Memory”

Use only current deviation from desired output to correct itself in the next cycle.

$$x(n+1) = x(n) + \text{error}\{y(n),y(n-1)\}$$

Class-II: “Feedback Regulators with Memory”

Use N previous traces of the “correction” steps in order to produce a better (future) adjustment.

$$x(n+1) = x(n) + \text{error}\{y(n),y(n-1)\} + \text{error}\{y(n-1),y(n-2)\} + \dots$$

Adaptive Systems – Taxonomy

Class-III: “Feedforward Regulators with No Memory”

Predict the next deviation from desired output to correct itself in the current cycle.

$$x(n+1) = x(n) + \text{pred.error}\{y(n+1),y(n)\}$$

Class-IV: “Feedforward Regulators with Memory”

Use N previous traces of the “correction” steps in order to produce a better (future) adjustment.

$$x(n+1) = x(n) + \text{pred.error}\{y(n+1),y(n)\} + \text{pred.error}\{y(n),y(n-1)\} + \dots$$

Adaptive Control and A.I.

- The behavioral model of an “intelligent” autonomous agent can be viewed as a “Black-Box”.
- **Inputs** are **sensor measurements** (smell, hear, see) and internal **states**/properties (energy, attitude).
- **Outputs** are **actions** that lead to “better” **states**.
- A **control model** can be designed to approximate an “optimal” behavioral pattern, i.e. a good “Black-Box”.
- If environment changes around the agent, the design process must be continuous, i.e. the control model must be **adaptive** (self-correcting).

Food for thought

- When should we use Adaptive AI ?
- When should we use Feedback or Feed-forward Regulators ?
- Do animals employ similar Adaptive AI ?
- How do the ARMA(N,M) models relate to the typical taxonomy of the Adaptive Systems ?
- In what real-world cases these control models are too “simplistic” and inadequate ?

P.C. – Readings

- John L. Casti, “Reality Rules II: Picturing the World in Mathematics – The Frontier”, John Wiley & Sons, 1997.
[see: ch.7]
- Tom Mitchell, “Machine Learning”, McGrawHill, 1997.
- D. Kirk, “Optimal Control Theory”, Prentice-Hall, 1970.
- A. V. Oppenheim, R. W. Schaffer, “Digital Signal Processing”, Prentice-Hall, 1975.