Introduction to Adaptive Control

– Adaptive Control: Identifier-Based
– Adaptive Control: Non–Identifier-Based
– Gain Scheduling
– Why Adaptive Control
– A Brief History

Introduction

- ***Adapt*** means to "change (oneself) so that one's behavior will conform to new or changed circumstances."

- The words *adaptive systems* and *adaptive control* have been used as early as 1950.

- We use the following specific definition of adaptive control: ***Adaptive control is the combination of a parameter estimator, which generates parameter estimates online, with a control law in order to control classes of plants whose parameters are completely unknown and/or could change with time in an unpredictable manner.***

Introduction

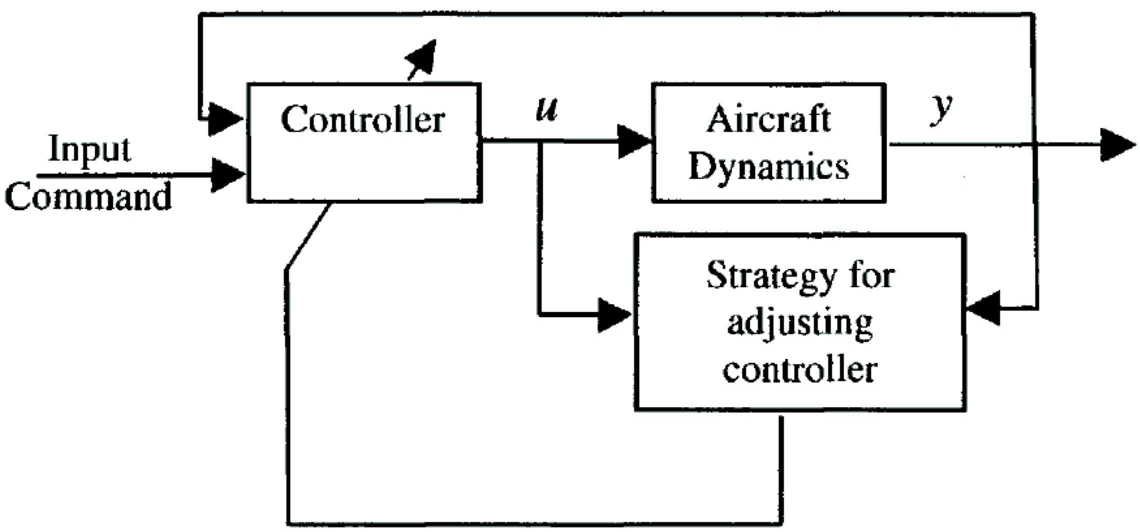
- The choice of the parameter estimator, the choice of the control law, and the way they are combined leads to different classes of adaptive control schemes.

- Adaptive control as defined above has also been referred to as ***identifier-based adaptive control*** in order to distinguish it from other approaches referred to as non-identifier-based, where similar control problems are solved without the use of an online parameter estimator.

- The design of autopilots for high-performance aircraft was one of the primary motivations for active research in adaptive control in the early 1950s.

Introduction

- The controller structure consists of a feedback loop and a controller with adjustable gains, as shown in following Figure.



General adaptive control structure for aircraft control.

Adaptive Control: Identifier-Based

The class of adaptive control schemes studied in this course is characterized by the combination of an ***online parameter estimator,*** with a ***control law***. The way the parameter estimator, also referred to as ***adaptive law***, is combined with the control law gives rise to two different approaches:

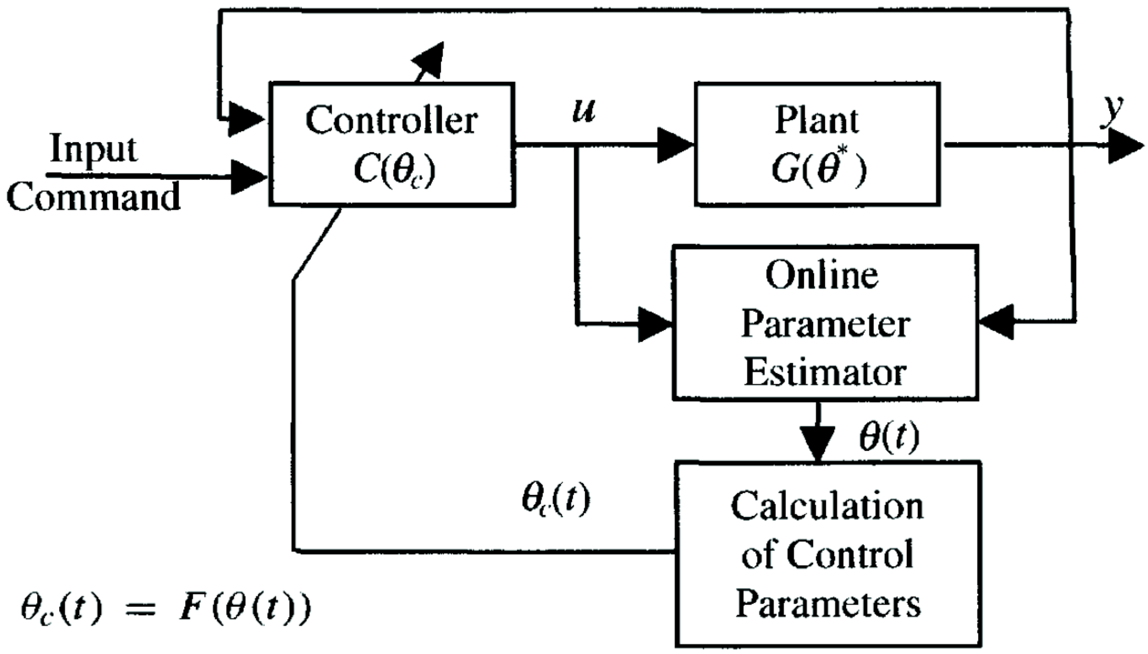
1- In the first approach, referred to as ***indirect adaptive control,*** the plant parameters are estimated online and used to calculate the controller parameters. In other words, at each time t, the estimated plant is formed and treated as if it is the true plant in calculating the controller parameters. This approach has also been referred to as ***explicit adaptive control,*** because the controller design is based on an explicit plant model.

Adaptive Control: Identifier-Based

2- In the second approach, referred to as ***direct adaptive control,*** the plant model is parameterized in terms of the desired controller parameters, which are then estimated directly without intermediate calculations involving plant parameter estimates. This approach has also been referred to as ***implicit adaptive control*** because the design is based on the estimation of an implicit plant model.

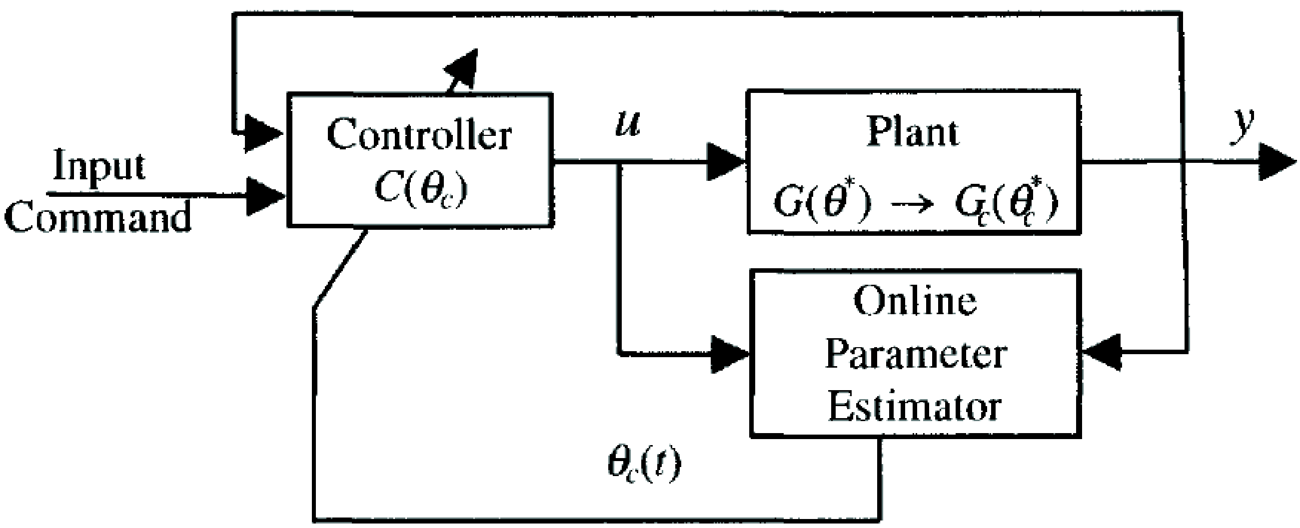
The basic structure of indirect adaptive control is shown in following Figure. The plant model $G(\theta^*)$ is parameterized with respect to some unknown parameter vector θ^*.

Adaptive Control: Identifier-Based



Indirect adaptive control structure.

Adaptive Control: Identifier-Based



Direct adaptive control structure.

Adaptive Control: Identifier-Based

In general, direct adaptive control is applicable to SISO linear plants which are ***minimum phase***, since for this class of plants the parameterization of the plant with respect to the controller parameters for some controller structures is possible.
Indirect adaptive control can be applied to a wider class of plants with different controller structures, but it suffers
from a problem known as the ***stabilizability*** *problem* explained as follows:
The controller parameters are calculated at each time *t* based on the estimated plant. Such calculations are possible, provided that the estimated plant is controllable and observable or at least stabilizable and detectable.

Adaptive Control: Identifier-Based

Since these properties cannot be guaranteed by the online estimator in general, the calculation of the controller parameters may not be possible at some points in time, or it may lead to unacceptable large controller gains.
So, solutions to this stabilizability problem are possible at the expense of additional complexity. Efforts to relax the minimum-phase assumption in direct adaptive control and resolve the stabilizability problem in indirect adaptive control led to adaptive control schemes where both the controller and plant parameters are estimated online, leading to combined direct/indirect schemes that are usually more complex .

Adaptive Control: Non-Identifier-Based

Another class of schemes that do not involve online parameter estimators is referred to as non-identifier-based adaptive control schemes. In this class of schemes, the online parameter estimator is replaced with search methods for finding the controller parameters in the space of possible parameters, or it involves switching between different fixed controllers, assuming that at least one is stabilizing or uses multiple fixed models for the plant covering all possible parametric uncertainties or consists of a combination of these methods.

We briefly describe the main features, advantages, and limitations of these non-identifier-based adaptive control schemes. Some of these approaches are relatively recent and research is still going on.

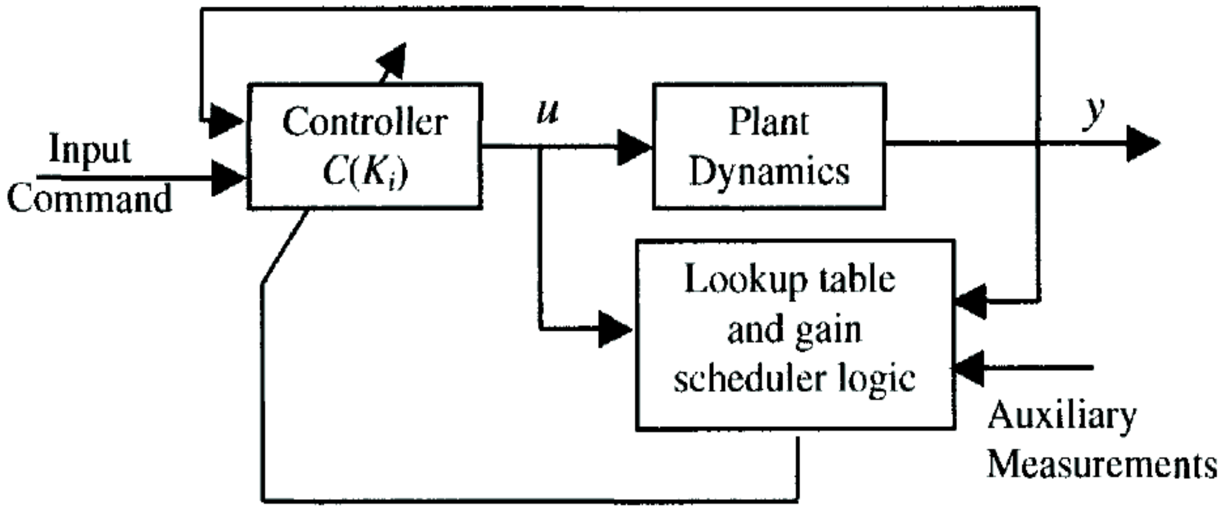
Adaptive Control: Non-Identifier-Based

- **Gain Scheduling**

The gain scheduler consists of a lookup table and the appropriate logic for detecting the operating point and choosing the corresponding value of control gains from the lookup table. With this approach, plant parameter variations can be compensated by changing the controller gains as functions of the input, output, and auxiliary measurements. The advantage of gain scheduling is that the controller gains can be changed as quickly as the auxiliary measurements respond to parameter changes. Frequent and rapid changes of the controller gains, however, may lead to instability; therefore, there is a limit to how often and how fast the controller gains can be changed.

Adaptive Control: Non-Identifier-Based

- **Gain Scheduling**



Gain scheduling structure.

Adaptive Control: Non-Identifier-Based

- **Gain Scheduling**

One of the disadvantages of gain scheduling is that the adjustment mechanism of the controller gains is precomputed offline and provides no feedback to compensate for incorrect schedules. A careful design of the controllers at each operating point to meet certain robustness and performance measures can accommodate some uncertainties in the values of the plant parameters. However large unpredictable changes in the plant parameters, may lead to deterioration of performance or even to complete failure.

Despite its limitations, gain scheduling is a popular method for handling parameter variations in flight control and other systems. While gain scheduling falls into the generic definition of adaptive control, we do not classify it as adaptive control due to the lack of online parameter estimation which could track unpredictable changes in the plant parameters.

Adaptive Control: Non-Identifier-Based

- **Multiple Models**
- **Search Methods, and**
- **Switching Schemes**

A class of non-identifier-based adaptive control schemes emerged over the years which do not explicitly rely on online parameter estimation. These schemes are based on search methods in the controller parameter space until the stabilizing controller is found or the search method is restricted to a finite set of controllers, one of which is assumed to be stabilizing. In some approaches, after a satisfactory controller is found it can be tuned locally using online parameter estimation for better performance.

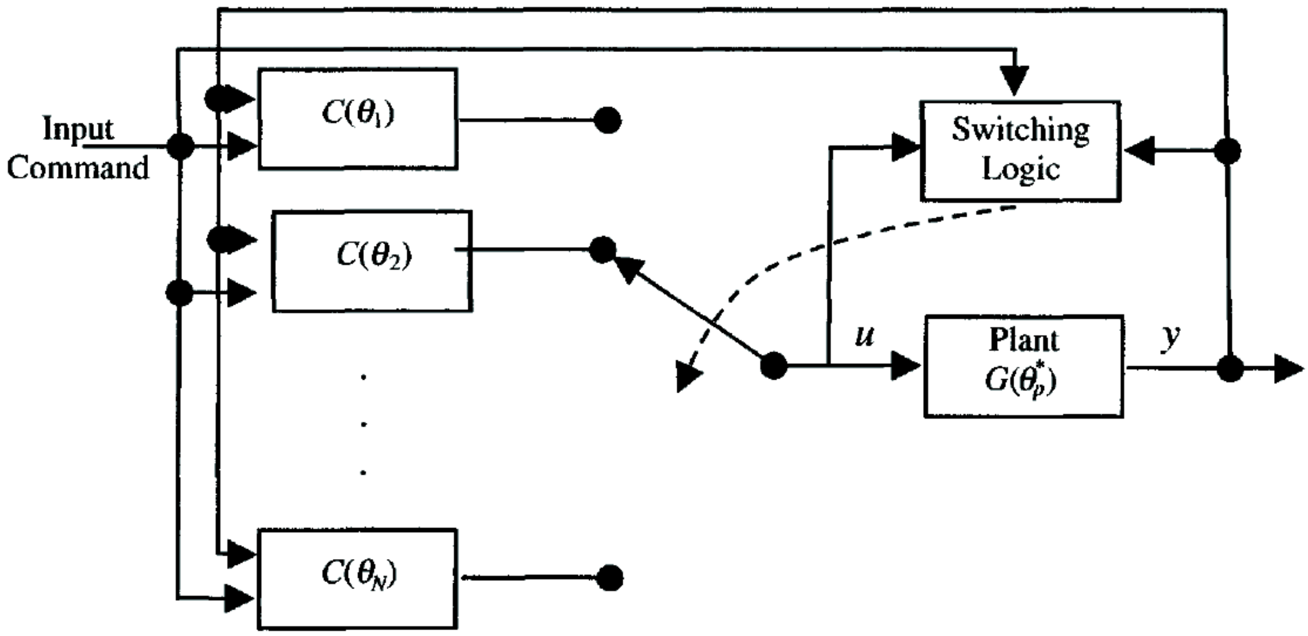
Adaptive Control: Non-Identifier-Based

- **Multiple Models**
- **Search Methods, and**
- **Switching Schemes**

Since the plant parameters are unknown, the parameter space is parameterized with respect to a set of plant models which is used to design a finite set of controllers so that each plant model from the set can be stabilized by at least one controller from the controller set. A switching approach is then developed so that the stabilizing controller is selected online based on the I/O data measurements. Without going into specific details, the general structure of this multiple model adaptive control with switching, as it is often called, is shown in next Figure.

Adaptive Control: Non-Identifier-Based

Multiple models adaptive control with switching



Why Adaptive Control

The choice of adaptive control as a solution to a particular control problem involves understanding of the plant properties as well as of the performance requirements. The following simple example illustrates situation where adaptive control is superior to linear control.

Consider the scalar plant

$$\dot{x} = ax + u,$$

where *u* is the control input and *x* the scalar state of the plant. The parameter *a* is unknown. We want to choose the input *u* so that the state *x* is bounded and driven to zero with time. If *a* is a known parameter, then the following linear control law can meet the control objective.

$$u = -kx, \quad k > |a|,$$

Why Adaptive Control

$$\dot{x} = ax + u, \quad u = -kx \quad \xrightarrow[k > \bar{a}]{\bar{a} \geq |a|} \quad x \to 0 \ as \ t \to \infty$$

In the absence of an upper bound for the plant parameter no linear controller could stabilize the plant and drive the state to zero.
As we will establish later , the adaptive control law

$$u = -kx, \quad \dot{k} = x^2,$$

guarantees that all signals are bounded and x converges to zero no matter what the value of the parameter a is. This simple example demonstrates that adaptive control is a potential approach to use in situations where linear controllers cannot handle the parametric uncertainty.

A Brief History

- Early 1950s, the design of **autopilots** for high-performance aircraft motivated intense research activity in adaptive control.
- 1958, 1961, **Model reference adaptive control** was suggested by Whitaker and coworkers in to solve the autopilot control problem.
- In the late 1980s to early 1990s, the use of neural networks as universal approximators of unknown nonlinear functions led to the use of **online parameter estimators** to "train" or update the weights of the neural networks.
- Adaptive control has a rich literature full of different techniques for design, analysis, performance, and applications. Several survey papers and books and thesis have already been published.
- Despite the vast literature on the subject, there is still a general feeling that adaptive control is a collection of unrelated technical tools and tricks.