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INSTITUTE OF SCIENCE AND TECHNOLOGY
(DEEMED TO BE UNIVERSITY)
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SCHOOL OF MECHANICAL ENGINEERING

DEPARTMENT OF MECHATRONICS ENGINEERING

UNIT – I - Adaptive Control System – SIC1612

SIC1612 - ADAPTIVE CONTROL SYSTEMS
UNIT - I

SATHYABAMA
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COURSE OBJECTIVES

- To make the student familiarize with adaptive control schemes and MRAS
- To identify the techniques of linear and nonlinear systems with unknown parameters
- To introduce stability robustness concepts with protection systems.

Adaptive Control System

UNIT 1 INTRODUCTION TO ADAPTIVE CONTROL SYSTEM 9 Hrs.

Definition of adaptive control system - functions of adaptive control - Different approaches to Adaptive Control - gain scheduling - Relay feedback

UNIT 2 IDENTIFICATION OF ADAPTIVE CONTROL 9 Hrs.

Conventional methods of Identifications - step response, impulse response, Bode plot - Identification of linear time-invariant systems - Adaptive observers - Sufficient richness condition for parameter convergence - Equation error and output error methods

UNIT 3 MODEL REFERENCE ADAPTIVE SYSTEMS (MRAS) 9 Hrs.

The need for MRAS - An over view of adaptive control systems - Mathematical description of MRAS - Design hypothesis - Equivalent representation of MRAS.

UNIT 4 CLASSIFICATION OF ADAPTIVE CONTROL 9 Hrs.

Definitions - Auto tuning - Types of adaptive control - Recent trends in self-tuning - Robustness studies - Multivariable systems - Model updating - General-purpose adaptive regulator

UNIT 5 ADAPTIVE PROTECTION 9 Hrs.

Need of Adaptive Protection in the system - Techniques for adaptive strategies in distance protection - Synchro-phasor based adaptive protection schemes - protection schemes - SCADA based protection systems - FTA - Testing of Relays.

Max. 45 Hours

Adaptive Control System

TEXT / REFERENCE BOOKS

1. Astrom K.J, Wittenmark B, Adaptive Control, Addison-Wesley, 2nd edition, 1995
2. Shankar Sastry, Marc Bodson, "Adaptive Control", Prentice Hall of India (P) Ltd., 1993.
3. Chalam V.V "Adaptive Control Systems - Techniques & Applications" - Marcel Dekker Inc
4. Chang C. Hong, Tong H. Lee and Weng K. Ho, Adaptive Control, ISA press, Research Triangle Park, 1993.

END SEMESTER EXAM QUESTION PAPER PATTERN

Max. Marks : 100 **Exam Duration : 3 Hrs.**

PART A : 2 Questions from each unit, each carrying 2 marks **20 Marks**

PART B : 2 Questions from each unit with internal choice, each carrying 16 marks **80 Marks**

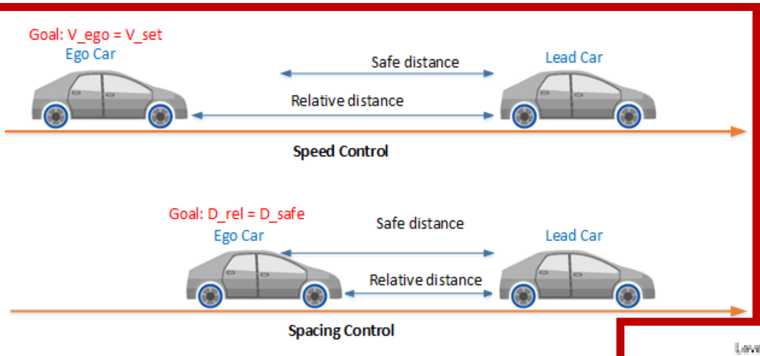
Adaptive Control System

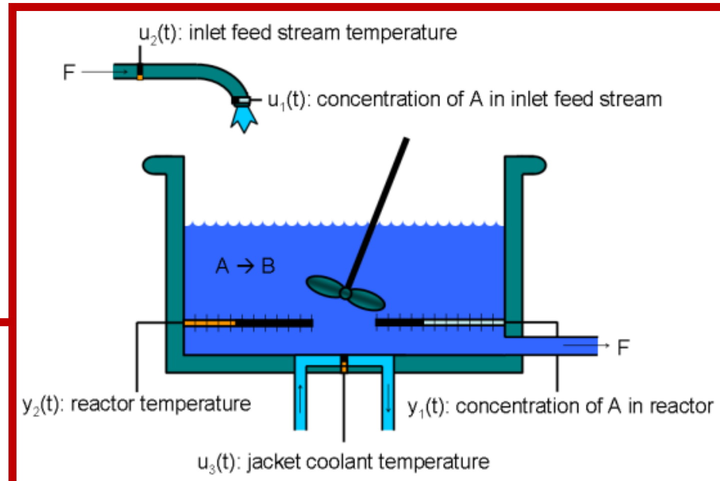
Adaptive control system adapts the parameters of the controller to changes in the parameters or structure of the controlled system in such a way that the entire system maintains optimal behavior according to the given criteria, independent of any changes that might have occurred.

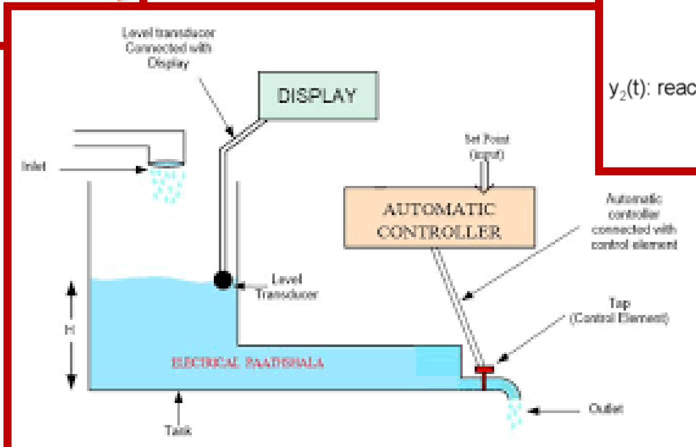
Adaptive control is the control method used by a controller which must adapt to a controlled system with parameters which vary, or are initially uncertain.

For example, as an aircraft flies, its mass will slowly decrease as a result of fuel consumption; a control law is needed that adapts itself to such changing conditions.

Adaptive control is different from robust control in that it does not need a priori information about the bounds on these uncertain or time-varying parameters; robust control guarantees that if the changes are within given bounds the control law need not be changed, while adaptive control is concerned with control law changing itself.







Adaptive Control System

ADAPTIVE CONTROL AND ITS APPLICATIONS IN THE INDUSTRY

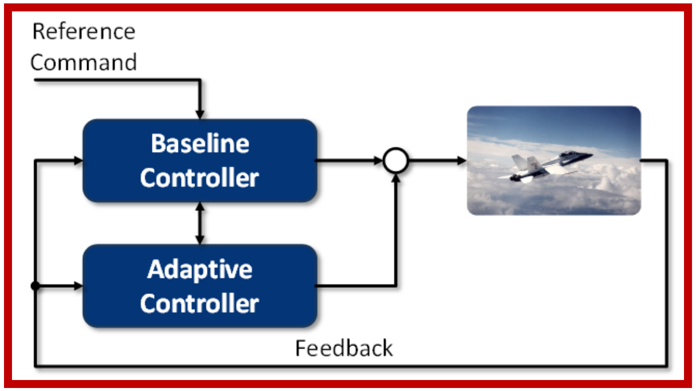
Adaptive control has been increasing its use in different sectors and industries since its beginnings in the **aerospace**, going through the control of vibrations until the use of **autonomous Systems and Unmanned Aerial Systems (UAS).** This is possible because its features permit to optimize the automations that are under its control, that is very attractive for industry.

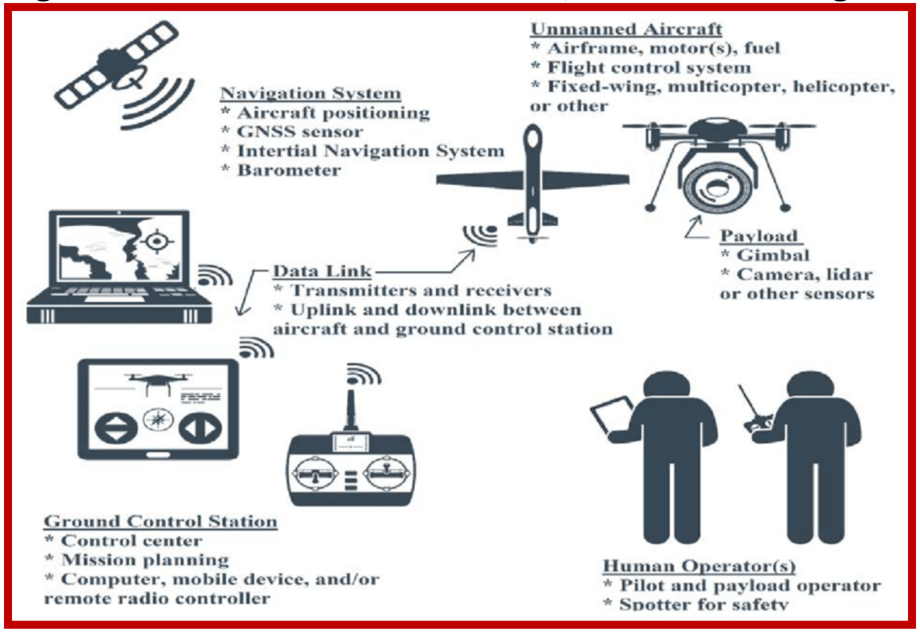
EVOLUTION OF THE ADAPTIVE CONTROL

Adaptive control was **originated in 1950**, when designing the **automatic control of an aircraft** whose dynamic was variable in the desired range of operations. For this reason, **conventional control was not capable to cover the range of operation** and it is created a gain scheduling technique.

Since then, adaptive control has been extended to new applications such as **drying ovens, active control of vibrations, efficient conditioning, robotics** permitting to control the process or even improve the efficiency that was performed with conventional controls.

Nowadays, one of the most important applications if the flight control of unmanned aircrafts, due to the changes in the flight dynamic

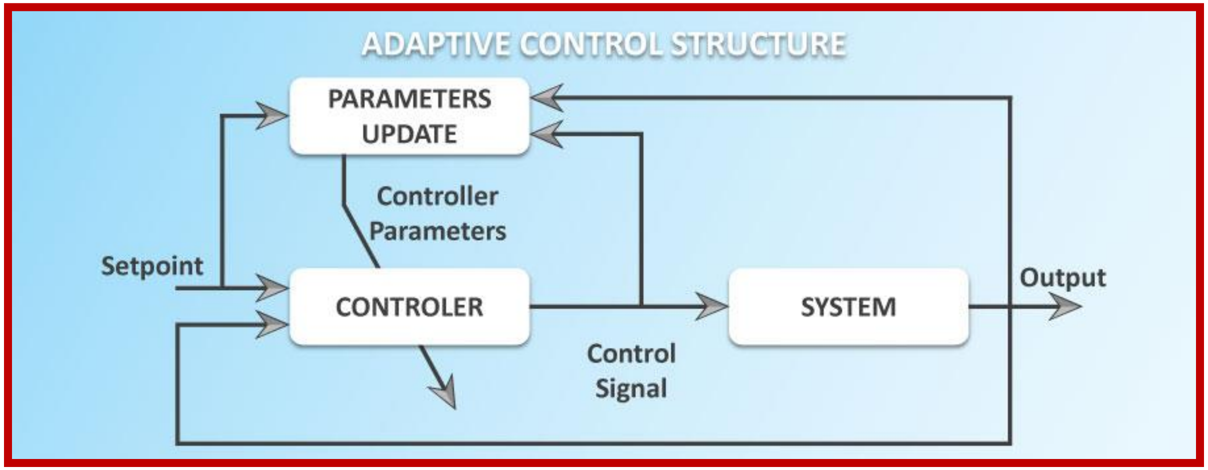




Adaptive Control System

WHAT IS THE ADAPTIVE CONTROL?

Adaptive control is a **set of techniques that permit to adjust the value of control parameters** in real time, permitting to **monitor controlled variables even if plant parameters are unknown or if they change over time**. This control is a special kind of non-lineal control, and the process can be split in two timelines: **rapid time (feedback loop)** and **slow time (variation of control parameters, which affects to automations).**



WHY AND ADAPTIVE CONTROL AND NOT A CONVENTIONAL ONE?

Conventional controllers are designed to adjust lineal and non-variable systems over time (LTI). This approach is true for fixed points of operations with small perturbations. **When this approximation stops being true, conventional controllers performance stops being good enough.**

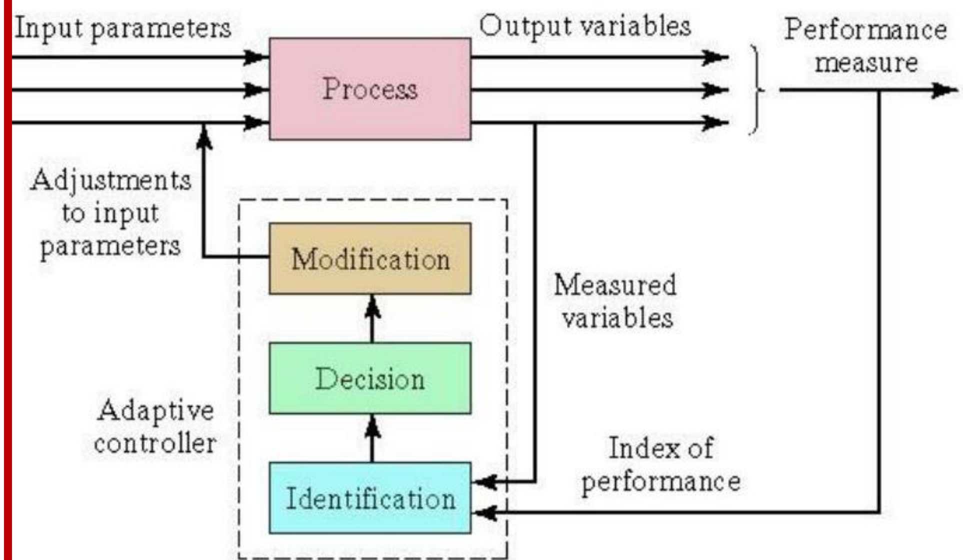
Adaptive control is capable to adapt itself changing control parameters, keeping a good control along the process.

In the UAS industry it should be preference to implement adaptive controls instead of conventional controls, since it permits to configure the controllers in a way that it can be automatically adapted to changing flight conditions.

For instance, during an UAS flight, its plant dynamic may change for different ranges of speed; in order to optimize the plant control, it is necessary a control rule capable to be adapted to this change in the system that some UAS autopilot can already manage.

Adaptive Control System

Adaptive Control System



- Because steady-state optimization is open-loop, it cannot compensate for disturbances
- Adaptive control is a self-correcting form of optimal control that includes feedback control
  - Measures the relevant process variables during operation (feedback control)
  - Uses a control algorithm that attempts to optimize some index of performance (optimal control)

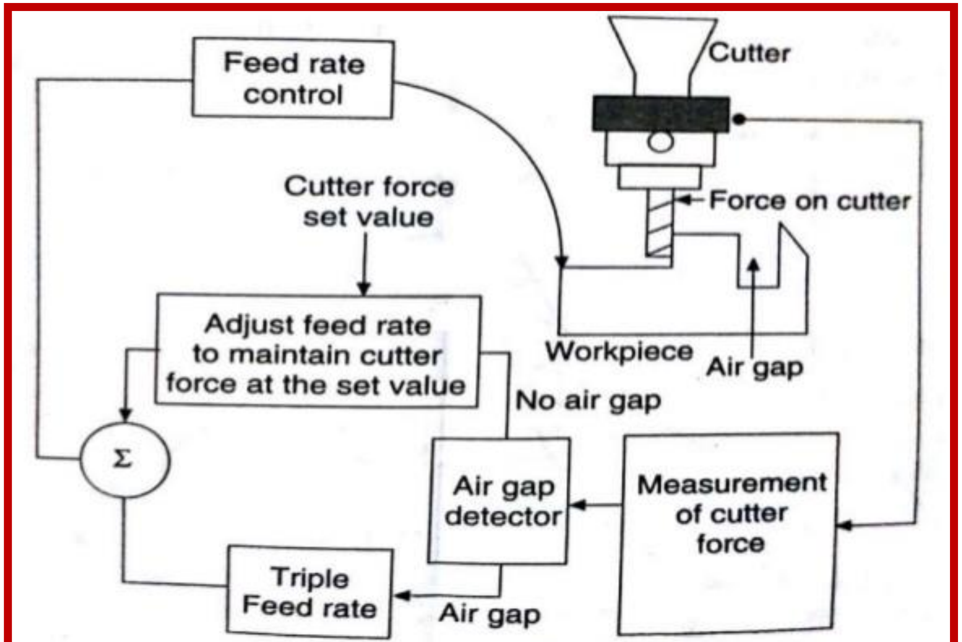
Three Functions in Adaptive Control

1. Identification function – current value of IP is determined based on measurements of process variables
2. Decision function – decide what changes should be made to improve system performance
   - Change one or more input parameters
   - Alter some internal function of the controller
3. Modification function – implement the decision function
   - Concerned with physical changes (hardware rather than software)

Adaptive Control Operates in a Time-Varying Environment

- The environment changes over time and the changes have a potential effect on system performance
  - Example: Supersonic aircraft operates differently in subsonic flight than in supersonic flight
- If the control algorithm is fixed, the system may perform quite differently in one environment than in another
- An adaptive control system is designed to compensate for its changing environment by altering some aspect of its control algorithm to achieve optimal performance

Adaptive Control System



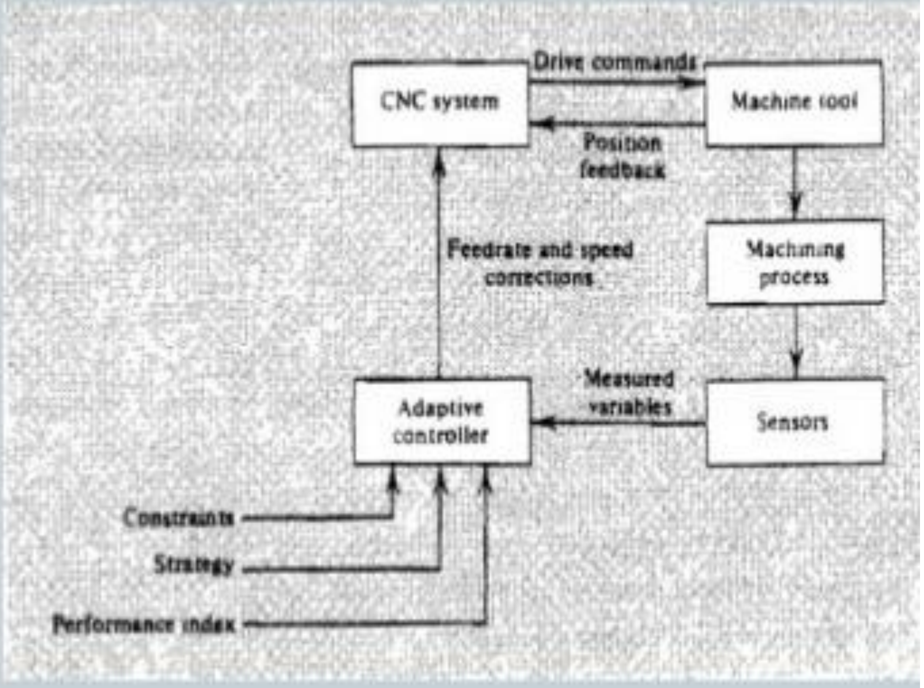
A typical adaptive control machining system.

- Adaptive control (AC) machining originated out of research in early **1970's** sponsored by **U.S Air Force**.
- The **initial** adaptive control systems were **based on analog devices**, representing the technology at that time.
- Today adaptive control uses **microprocessor** based controls and is typically **integrated** with an existing **CNC system**.

- Adaptive control system is a **logical extension** of the CNC-mechanism.
- In CNC mechanism the cutting speed and feed rates are prescribed by the **part programmer**.
- The determination of these operating parameters **depends on the Knowledge and experience** of programmer regarding the work piece, tool materials, coolant conditions and other factors.
- By contrast in adaptive control machining, there is **improvement** in the production rate and reduction in the machining cost as a result of calculating and setting of optimal parameters **during machining**.

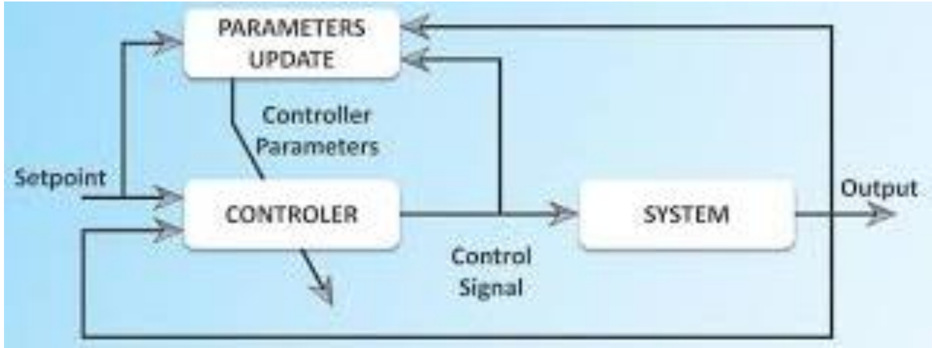
Adaptive Control System

- For a machining operation the term AC denotes **control systems** that **measures** certain **output variables** and uses to control speed or feed.
- Some of the process variables that have been used in AC machining systems include spindle deflection or force, torque, cutting temperature and horse power.



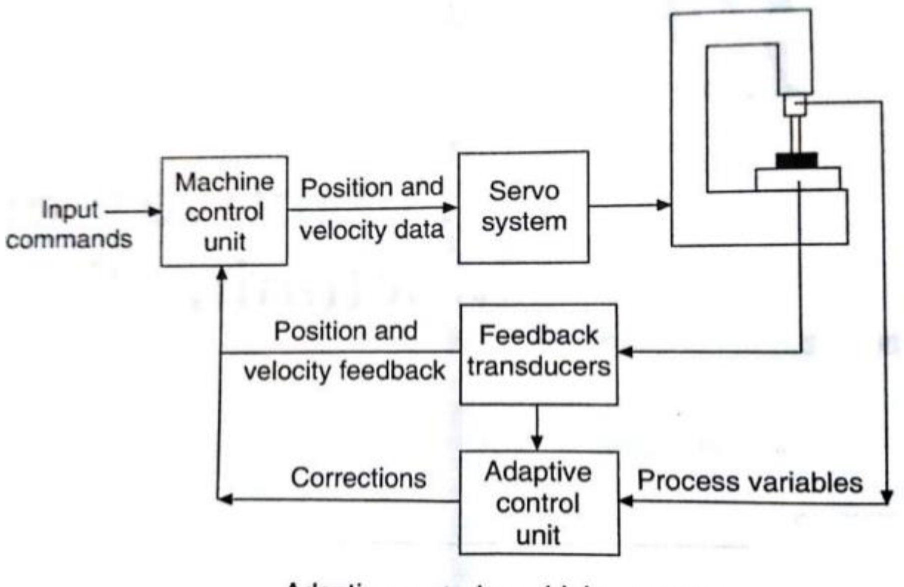
Adaptive Control System

- The adaptive control is basically a **feedback system** that treats the CNC as an internal unit and in which the machining variables **automatically** adapt themselves to the actual conditions of the machining process.
- Note:- IP (**Performance Index**) is usually an economic function such as max production rate or minimum machining cost.



The three **functions** of adaptive control are:

- Identification function.
- Decision function.
- Modification function.
- The main idea of AC is the **improvement of the cutting process** by **automatic** on line determination of speed and/or cutting.
- The AC is basically **a feedback system** in which cutting **speed and feed automatically adapt themselves** to the actual condition of the process and are varied accordingly to the changes in the work conditions as work progresses.



Adaptive control machining system.

Adaptive Control System

IDENTIFICATION FUNCTIONS

- This involves determining the **current performance** of the process or system .
- The identification function is concerned with **determining the current value** of this performance measure by **making use of the feedback data** from the process.

DECISION FUNCTION

- Once the system performance is determined, the next function is to decide how the control mechanism should be **adjusted** to **improve** process performance.
- The decision procedure is carried out by means of a pre-programmed logic provided by the designer.

MODIFICATION FUNCTION

- The third AC function is to implement the decision.
- While the decision function is a logic function, modification **is concerned with a physical or mechanical change** in the system.
- The modification **involves changing the system parameters or variables** so as to drive the process towards a more **optimal state**.

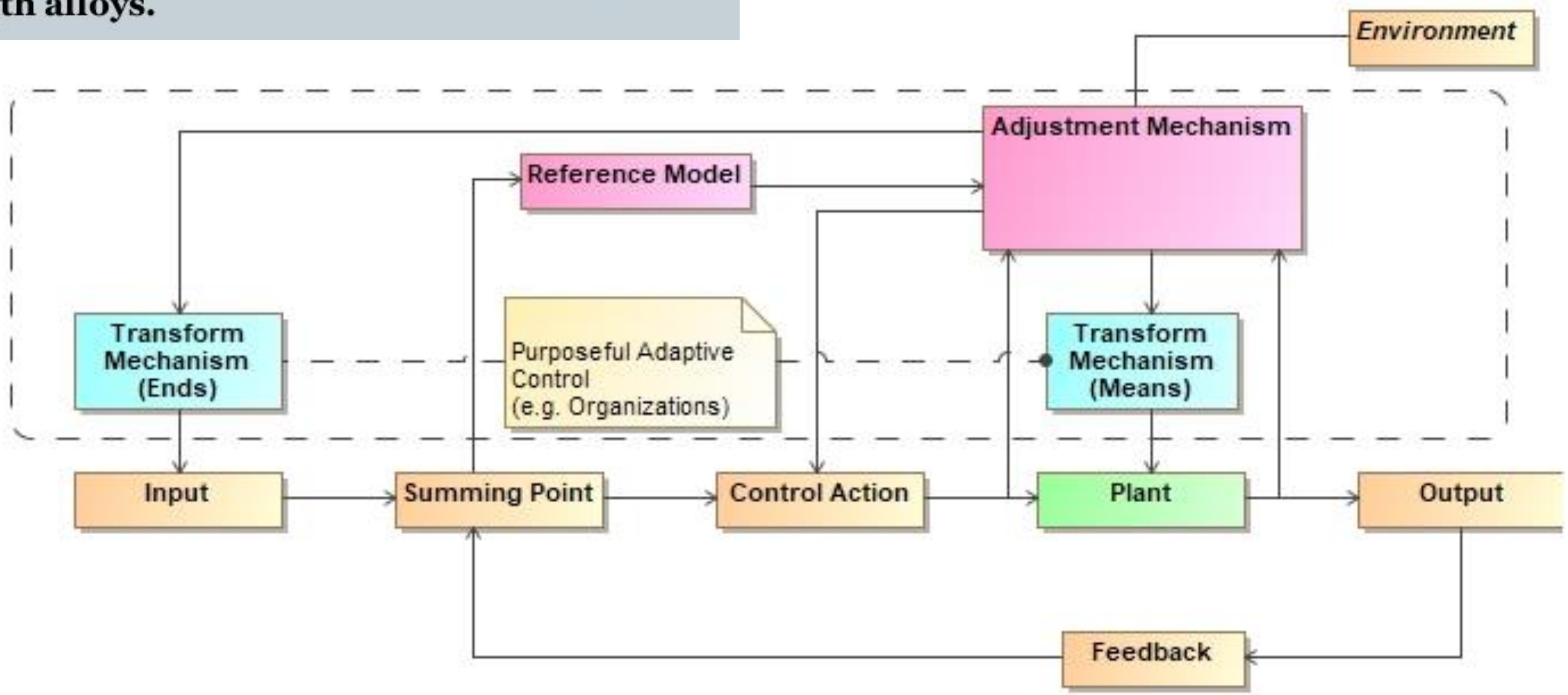
Adaptive Control System

WHERE TO USE ADAPTIVE CONTROL

- Adaptive control is not suitable for every machining situation.
- In general, the following characteristics can be used to identify situations where adaptive control can be beneficially applied.
- The **in-process time** consumes a significant portion of the machining cycle time.
- There are significant **sources of variability** in the job for which AC can compensate.
- The **cost of operating** the machine tool is high.
- The typical jobs involve steels, titanium and **high strength alloys.**

In practice the AC system of machine tools can be classified into two types:

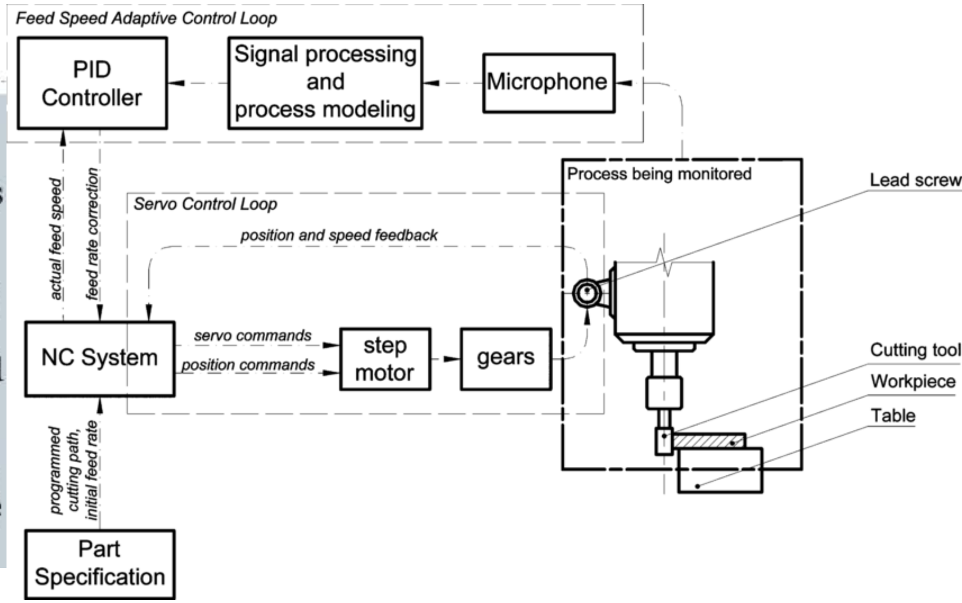
- AC with optimization (**ACO**)
- AC with constrains (**ACC**)
- Geometric Adaptive Control (**GAC**)

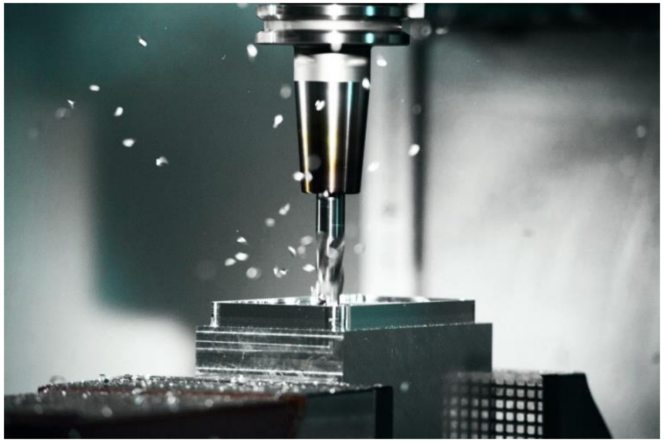


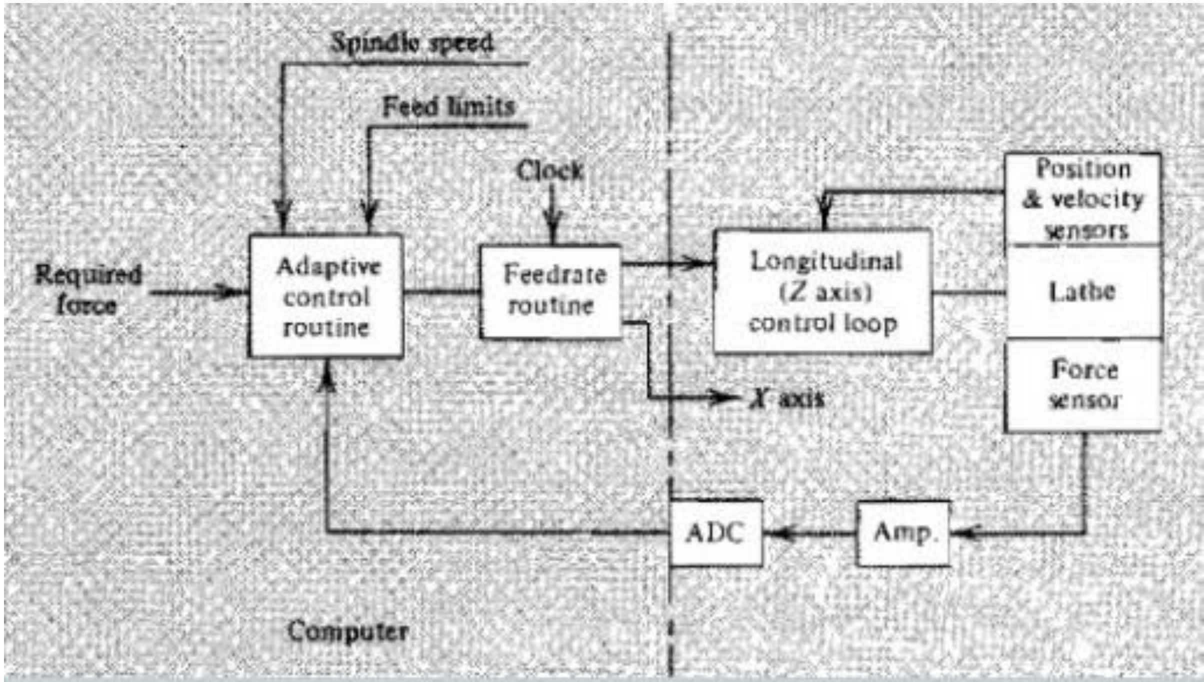
Adaptive Control System

ACC

- ACC are systems in which **machining conditions** such as spindle speed or feed rate **are maximized** within the **prescribed limits** of machines and tool **constrains** such as maximum torque, force or horse power.
- In AC system the correct feed and speed are **automatically found** and it is not necessary to spend efforts on calculations of optimum feeds and speeds.
- ACC systems do not utilize a performance index and are based on **maximizing a machining variable** (e.g., feed rate) subject to process and machine constraints (e.g., allowable cutting force on the tool, or maximum power of the machine).
- The **objective** of most ACC types of systems is to increase the MRR during rough cutting operations.

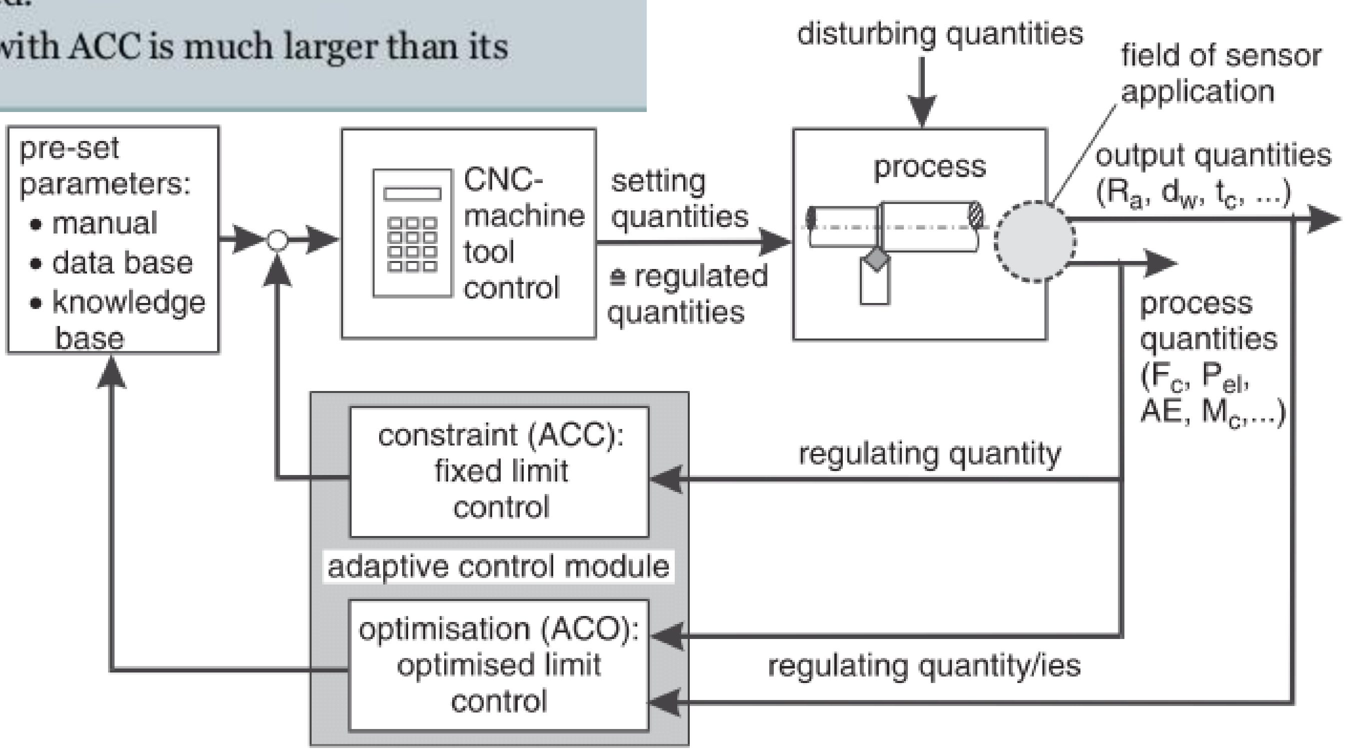






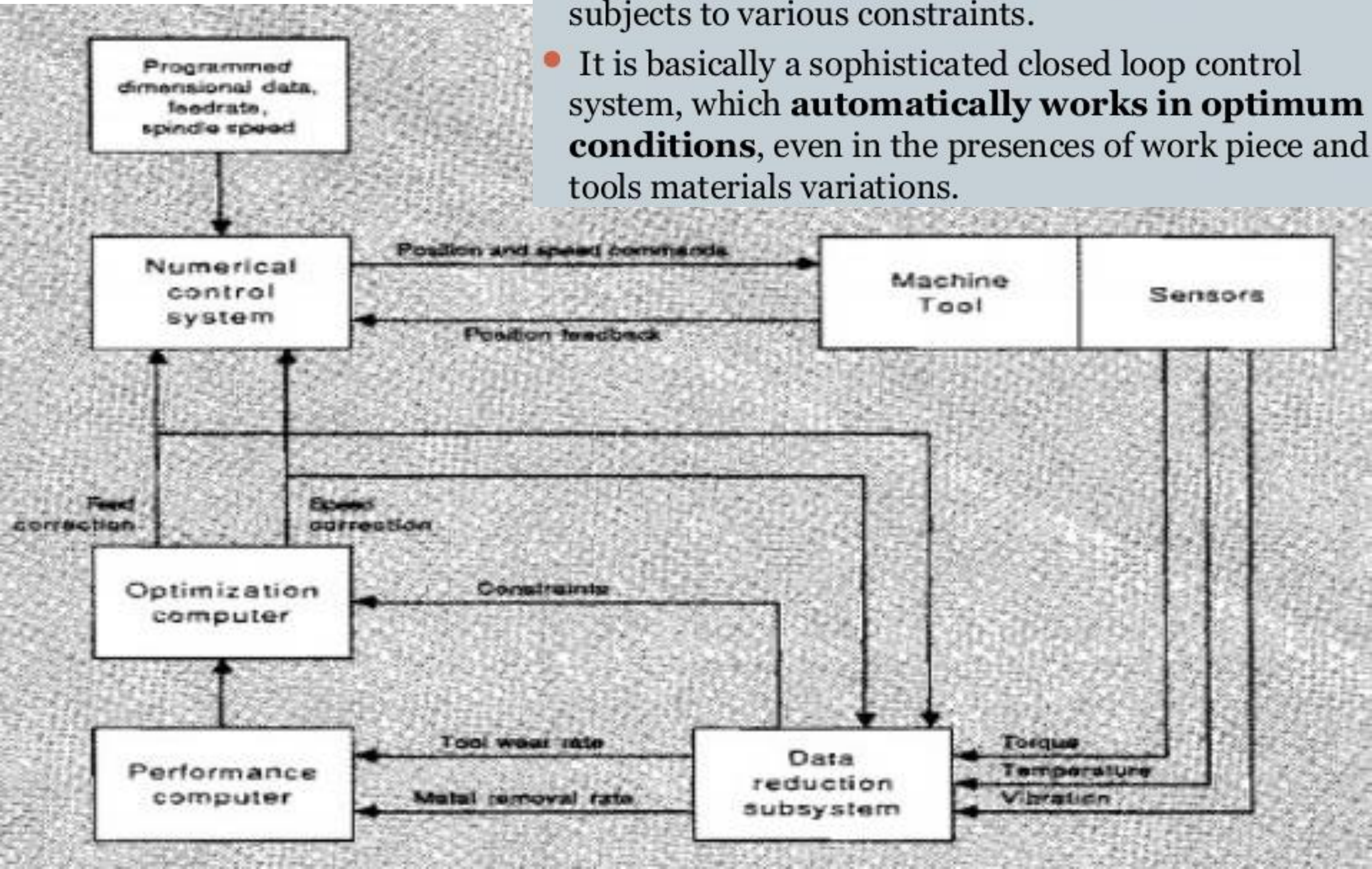
Adaptive Control System

- For example, to **maximize** the machining feedrate while maintaining a **constant load** on the cutter, despite variations in width and depth of cut.
- In a **normal CNC** system, the feedrate is programmed to accommodate the largest width and depth in a particular cut, and this small feedrate is maintained along the entire cut. As a result the machining rate is reduced.
- By contrast, with the **ACC system**, the maximum allowable load (e.g., cutting force) on the cutter is programmed.
- As a result, when the width or depth of cut are small the feedrate is high; when either the width or depth of cut (or both) are increased, the feedrate is automatically reduced, and consequently the allowable load on the cutter is not exceeded.
- The **result** is, the average feed with ACC is much larger than its programmed counterpart.



Adaptive Control System

- The ACO Systems for N/C machine tools is a control system that **optimizes performance index** subjects to various constraints.
- It is basically a sophisticated closed loop control system, which **automatically works in optimum conditions**, even in the presences of work piece and tools materials variations.



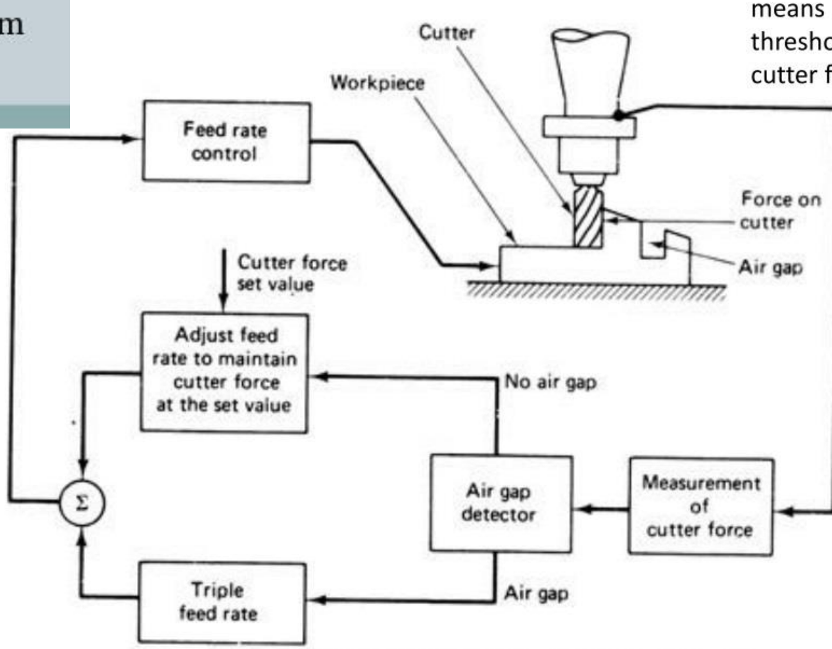
Adaptive Control System

Drawback of ACO

- The **main problem** is that this require on-line measurement of tool wear.
- So far there have been no industrially acceptable methods developed for the direct measurement of tool wear.
- Indirect measurement assumes that tool wear is proportional to other measurable variables such as cutting forces and temperatures.
- The drawback of using these indirect measurements is that variations in their values can be caused by process variations other than tool wear, such as workpiece hardness or cutting conditions.
- Thus making it difficult to identify the tool wear effect from the effect of the other parameter variations on the measurements.

ADAPTIVE CONTROL

Airgap is sensed by means of low threshold value of cutter force.



Configuration of typical adaptive control machining system that uses cutter force as the measured process variable.

Adaptive Control System

GEOMETRIC ADAPTIVE CONTROL

- GAC are typically **used in finish machining** operations.
- In GACs the part quality is maintained in real time by compensating for the deflection and wear of cutting tools.
- The objective of GAC is to achieve:-
- (1) the required dimensional accuracy and
- (2) a consistency of surface finish of machined parts

despite tool wear or tool deflection

Drawback of GAC

- Both the dimensional accuracy and the surface finish are affected by the flank wear and the crater wear of the tools which deteriorate during cutting.
- These variables cannot be measured in real time; neither can they be accurately predicted from off-line tool testing.

Adaptive Control System

Need for Adaptive Control

1. The key reason is that most of the processes are nonlinear. The control loops are generally designed to maintain the controlled variable at its set point by compensating for all disturbance occurring in the process. The controller performance is optimum only for a particular range in which the process is linearized. Once the process starts to operate beyond the linearized range, the controller fails to produce desired performance. It is because of the fact that the parameters of the controller is not suitable for the current operating conditions.

2. The changes in transfer function of process which occurs due to parameter variations or variation in the coefficients or wear and tear of important components.

3. The nature and magnitude of disturbances vary with time. There may be an occurrence of an unpredictable and unknown disturbance in the process.

4. There may be a change in nature of inputs to the process and the properties of raw materials.

In all the above cases, a conventional controller cannot perform at a satisfactory level. This demands the need for a special type of controller that adapt in accordance with the uncertainties in the process and in turn Adaptive Control

Adaptive Control System

Types of Adaptive Control

There are two major approaches to determine the controller parameters adaptation. They are,

1. Programmed or Gain Scheduled Adaptive Control

The Programmed Adaptive Control is compared to feed forward compensation because it adjust the controller parameters based on the measurement of an auxiliary variable and the knowledge of operating conditions of process. Also, there is no feedback to check the correctness of adaptation.

2. Self-Adaptive Control

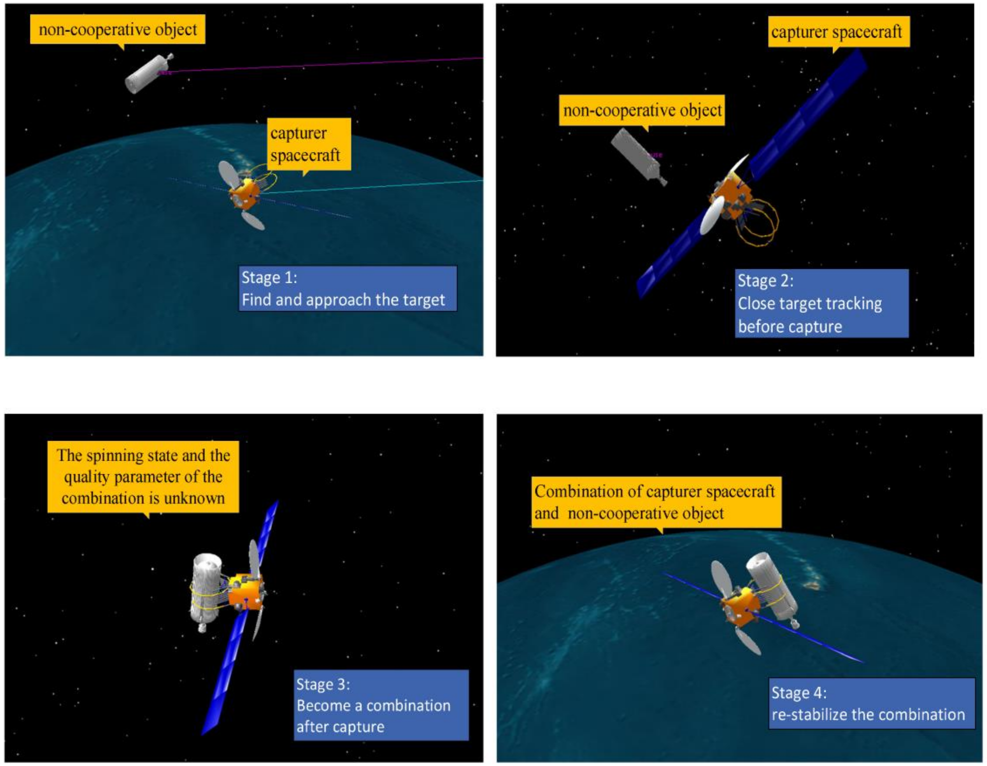
The Self-Adaptive Control is comparable to feedback compensation because the adaptation of controller parameters is based on the measurement of closed loop performance and aim to optimize it. Model Reference Adaptive Control (MRAC) and Self Tuning Regulator (STR) are two mechanisms that come under self-adaptive control.

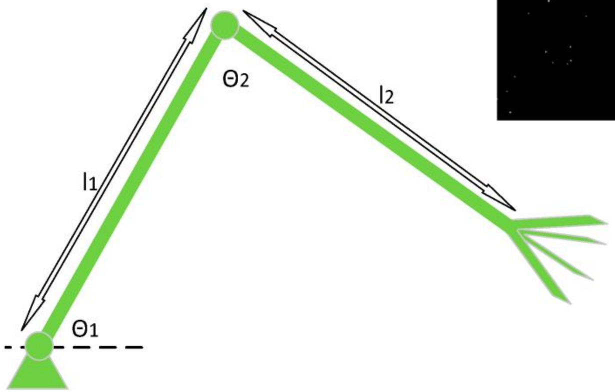
Adaptive Control System

Applications of Adaptive Control

1. Adaptive control is used in the robotic manipulators of robotic systems which demands high positioning accuracy.

2. Adaptive control is used for altitude control of satellites. The observation satellites should be operated at lower altitudes where the air-drag makes the quick reorientation of satellite is necessary to increase the observation time.



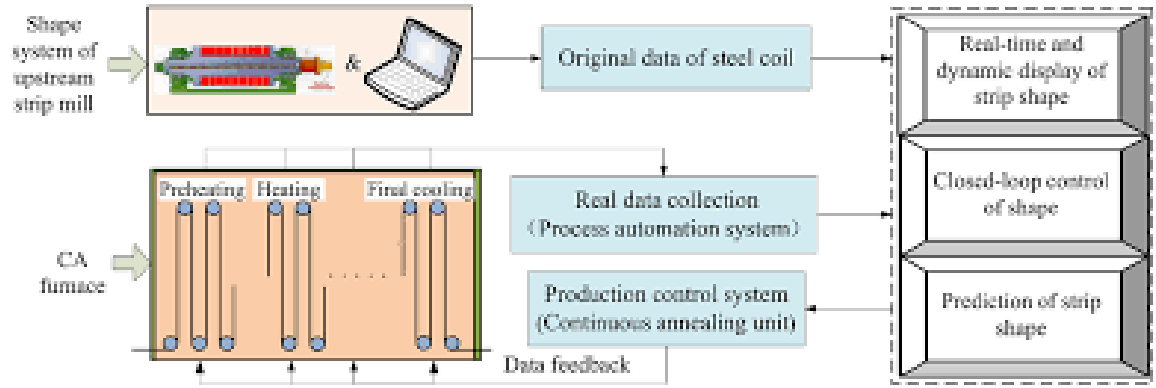


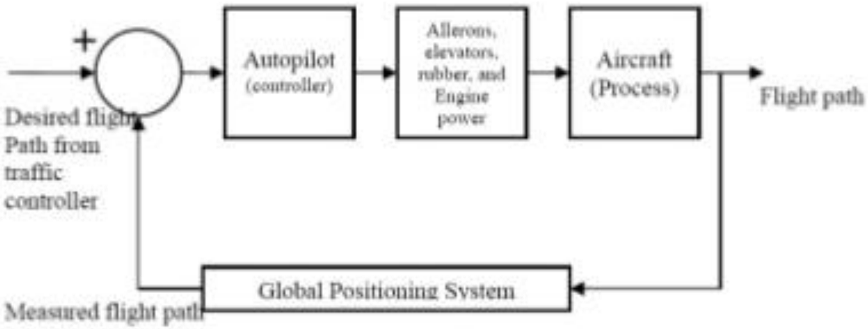
Adaptive Control System

Applications of Adaptive Control

3. Adaptive control is used in the autopilot of air crafts and steering control of ships.

4. Adaptive control is used in the control of strip temperature for the continuous annealing and processing in metallurgical processes.





Autopilot Control System

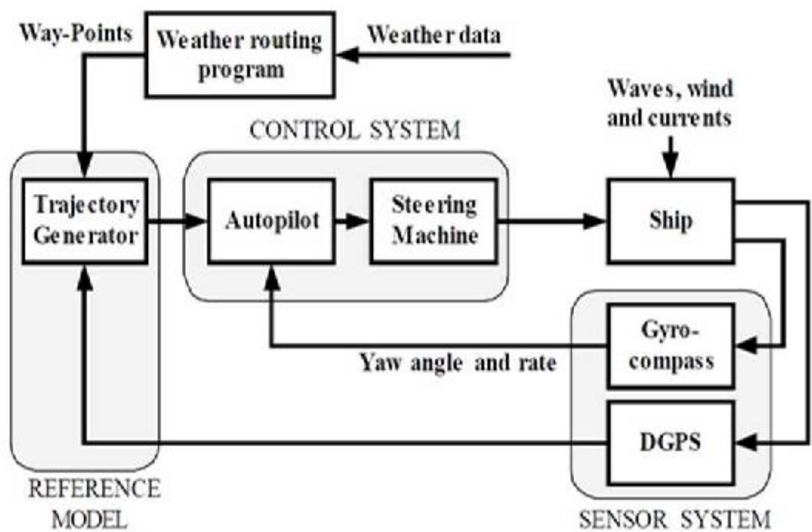
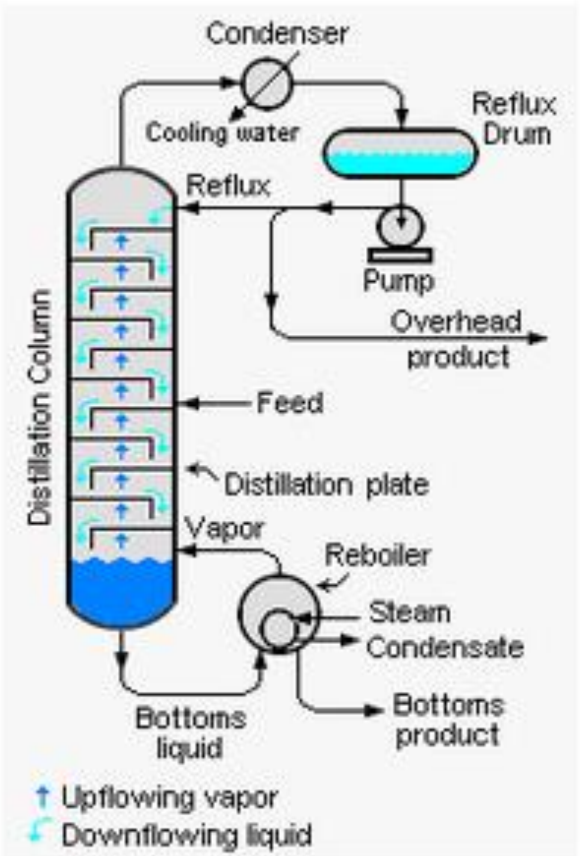


Fig. 1. Steering control

Applications of Adaptive Control

5. Adaptive control is used in distillation columns to provide high product quality and a considerable reduction of thermal energy usage.

6. Adaptive control is used to stabilize PID based pH control system in chemical industries. Without adaptive control, the process gain (K_p) increases as the pH value becomes neutral and it leads to change in total loop gain and finally to instability of loop. The adaptive control keeps the total loop gain at the desired value (usually 0.5) by lowering the controller gain (K_c).



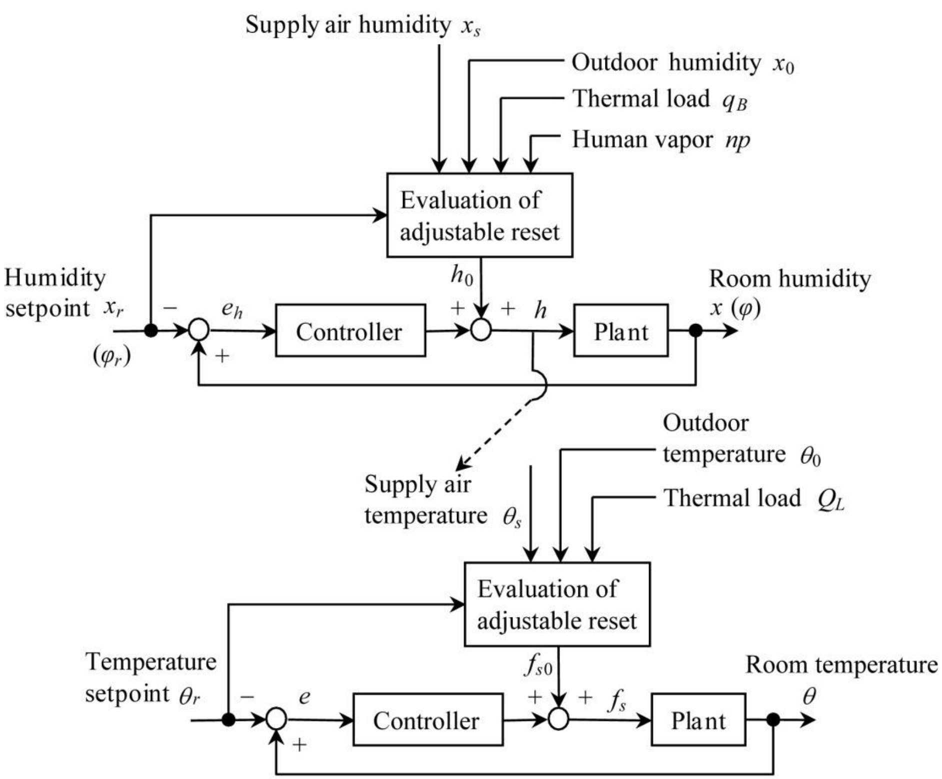
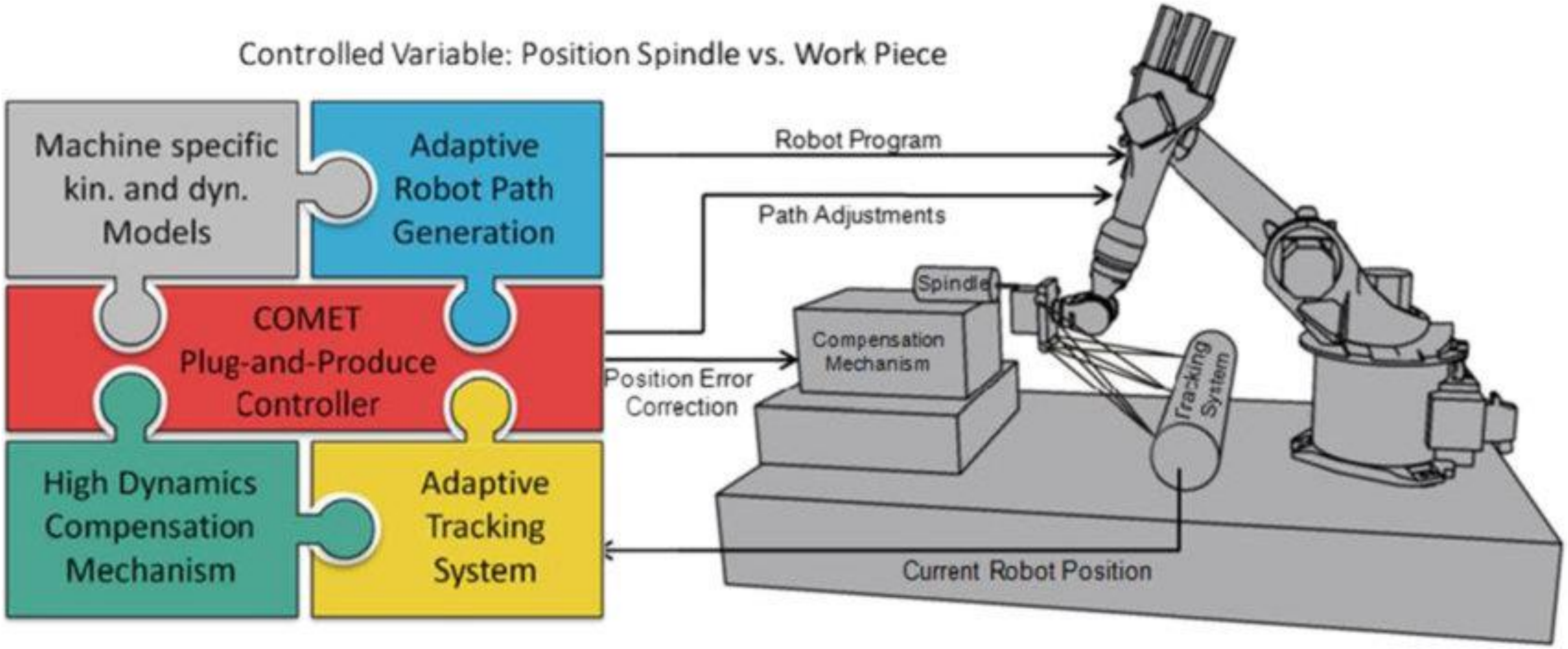


Figure 3 Overall of the combined control system

Adaptive Control System



Benefits of AC

- Increased production rates.
- Increased tool life.
- Greater part protection.
- Less operator intervention.

Limitations

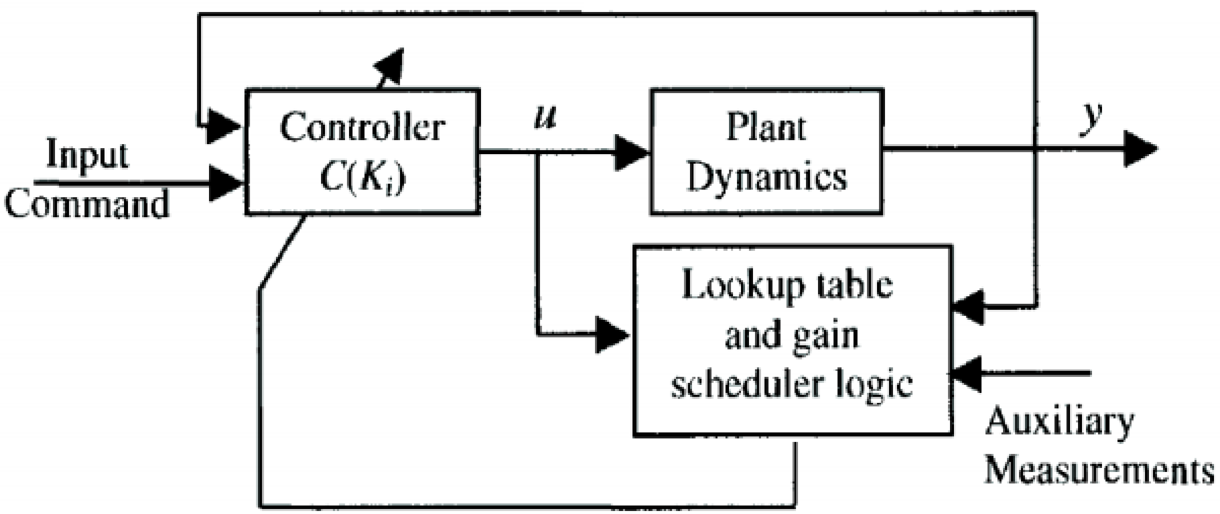
- A major drawback is the unavailability of suitable sensors that have a reliable operation in a manufacturing environment . (Tool wear sensor).
- Another problem is the interface of an AC system with CNC units. As yet, manufacturers have not standardized interfaces.

Adaptive Control System

- **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.

- **Gain Scheduling**



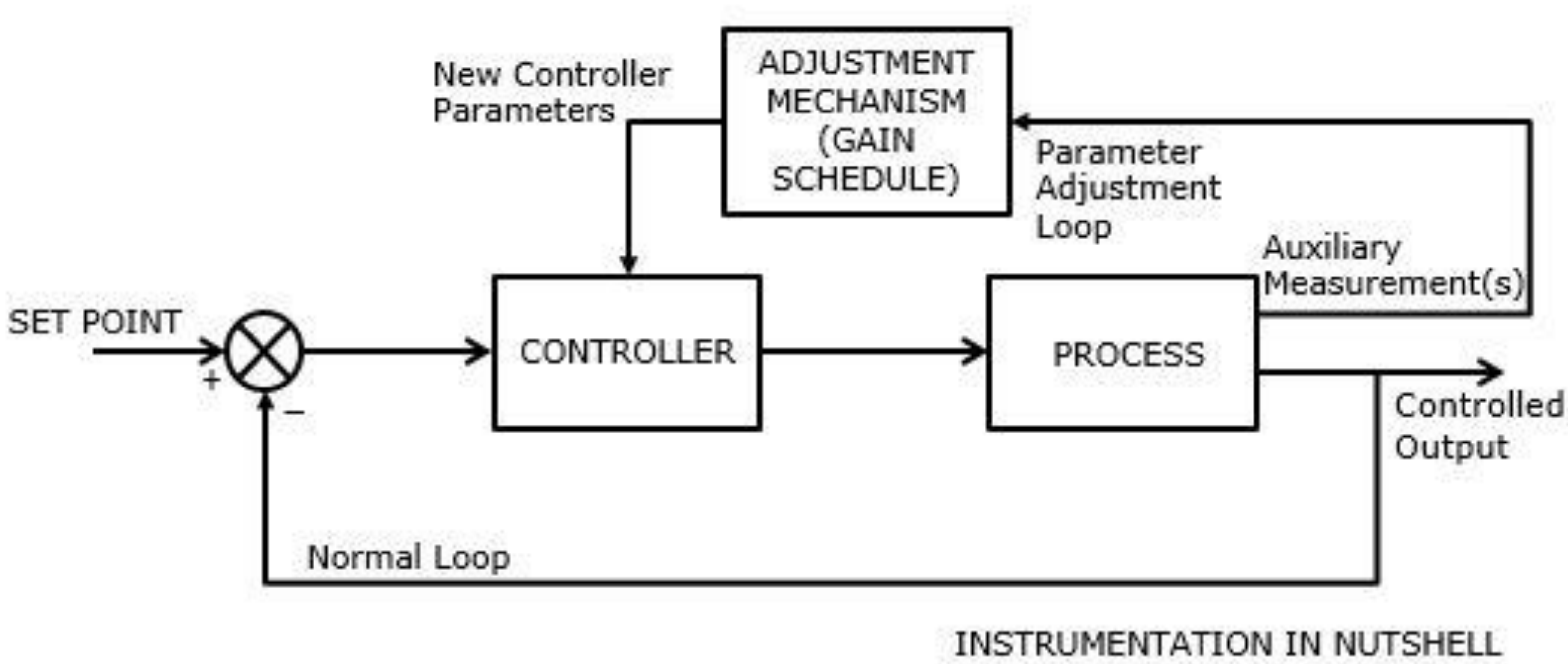
Gain scheduling structure.

Adaptive Control System

Programmed or Gain Scheduled Adaptive Control

The Programmed Adaptive Control adjusts the controller parameters based on the measurement of an auxiliary variable that affects the control loop gain in a predictable manner or by the known nonlinear behavior of the process for various operating conditions.

The Gain Scheduling gives the rough controller parameters and adaptive control does the tuning of controller parameters.



Block Diagram of Gain Scheduled Adaptive Control

Adaptive Control System

If the process exhibits predictable variations, then the adaptation of controller parameters can be programmed or scheduled.

The variations in the process are identified by the measurement of auxiliary variables.

The auxiliary variables are to be selected in such a way that it correlates well with the process dynamics changes.

The appropriate values of controller parameters are mapped to the values of the auxiliary process variable.

The programmed adaptive control system is composed of two loops. One is the normal feedback control loop.

The other one is the parameter adjustment loop that adjusts the controller parameters using the values of gain programmed into the adjustment mechanism.

The parameter adjustment loop is slower than the normal feedback loop.

Adaptive Control System

Advantage of Gain Scheduling

The advantage of gain scheduling is that the controller parameters are changed quickly in response to the changes in process dynamics. It requires no estimation as the values of controller parameters are programmed in advance.

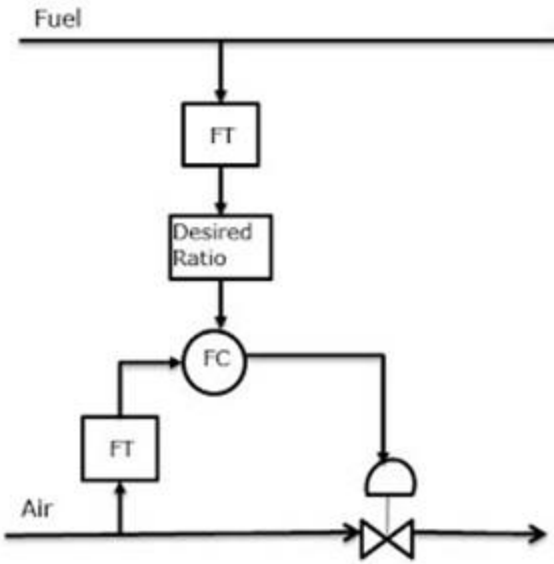
Limitations of Gain Scheduling

1. The design of programmed adaptive control system is time-consuming because the controller parameters have to be determined for all possible operating conditions and have to be checked by simulations.
2. There is no feedback to compensate for an incorrect adaptation making it comparable to feed forward or open-loop compensation.

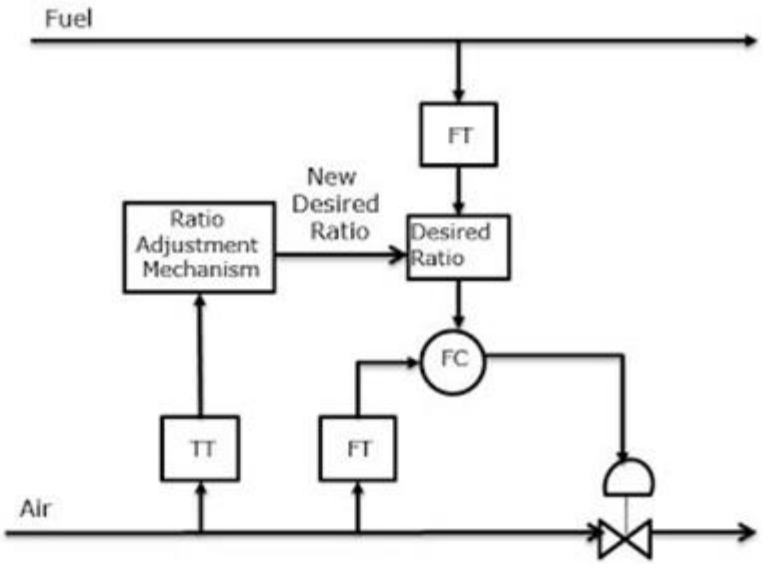
Adaptive Control System

Example

Programmed Adaptive Control for a Combustion System



Ratio Control for a Combustion System



Adaptive Ratio Control Mechanism for a Combustion System

- The air-fuel ratio is to be kept at an optimal value in a combustion system to attain high efficiency.
- A ratio control mechanism can be used to maintain the air-fuel ratio.
- The need for adaptive control arises because the optimal value of the air-fuel ratio depends on the temperature of the air.
- The temperature of the air is a variable that changes at any time (non-stationary process) in the process.
- The programmed adaptive control can be implemented by determining the optimal value of the air-fuel ratio for different air temperatures through experiments.
- The air temperature is measured (auxiliary measurement) and it used to adjust the value of the air-fuel ratio.
- It is to be noted that a ratio control mechanism is a form of feed forward compensation.

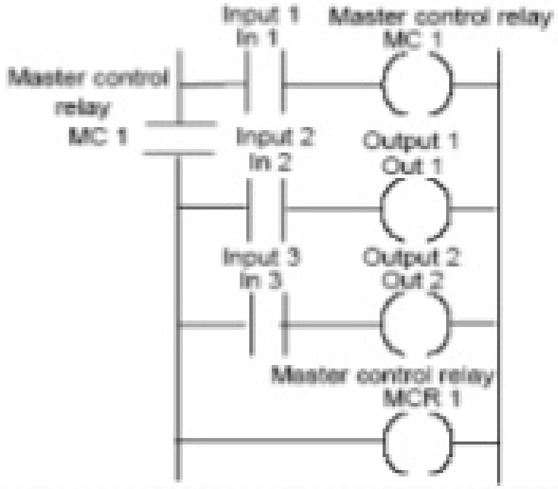
Master control relay

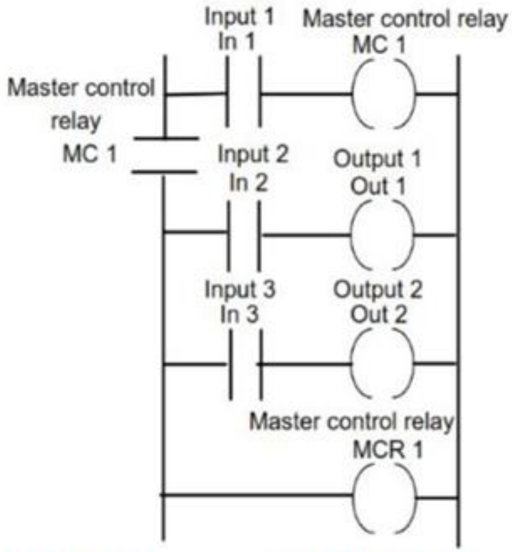
With no input to input 1,

- the output internal relay MC 1 is not energized and so its contacts are open.
- This means that all the rungs between where it is designated to operate and the rung on which its reset MCR or another master control relay is located are switched off.
- Assuming it is designated to operate from its own rung, then we can imagine it to be located in the power line in the position shown and so rungs 2 and 3 are off.

When input 1 contacts close,

- the master relay MC 1 is energized.
- When this happens, all the rungs between it and the rung with its reset MCR 1 are switched on.
- Thus outputs 1 and 2 cannot be switched on by inputs 2 and 3 until the master control relay has been switched on.
- The master control relay 1 acts only over the region between the rung it is designated to operate from and the rung on which MCR 1 is located.





MASTER CONTROL RELAY – to control large number of outputs – turn on/off whole section of ladder diagram

Master control relay

- When large numbers of outputs have to be controlled, it is sometimes necessary for whole sections of ladder diagrams to be turned on or off when certain criteria are realized. This could be achieved by including the contacts of the same internal relay in each of the rungs so that its operation affects all of them.
- An alternative is to use a master control relay.
- To program an internal relay M100 to act as master control relay contacts the program instruction is: MC M100
- To program the resetting of that relay, the program instruction is: MCR M100

Adaptive Control System

ASSIGNMENT – 1 (10 – 12 PAGES) WITH REFERENCE

Review on Adaptive Control System (ACS)

Industrial Applications / Food processing Industry / Power generation Sector / Manufacturing Sector / New Product Development etc…

Introduction to ACS

- **ACS Approaches / Techniques**
- **ACS problem faced while implementing**
- **ACS Implementation**
- **ACS Applications**
- **ACS Limitations**

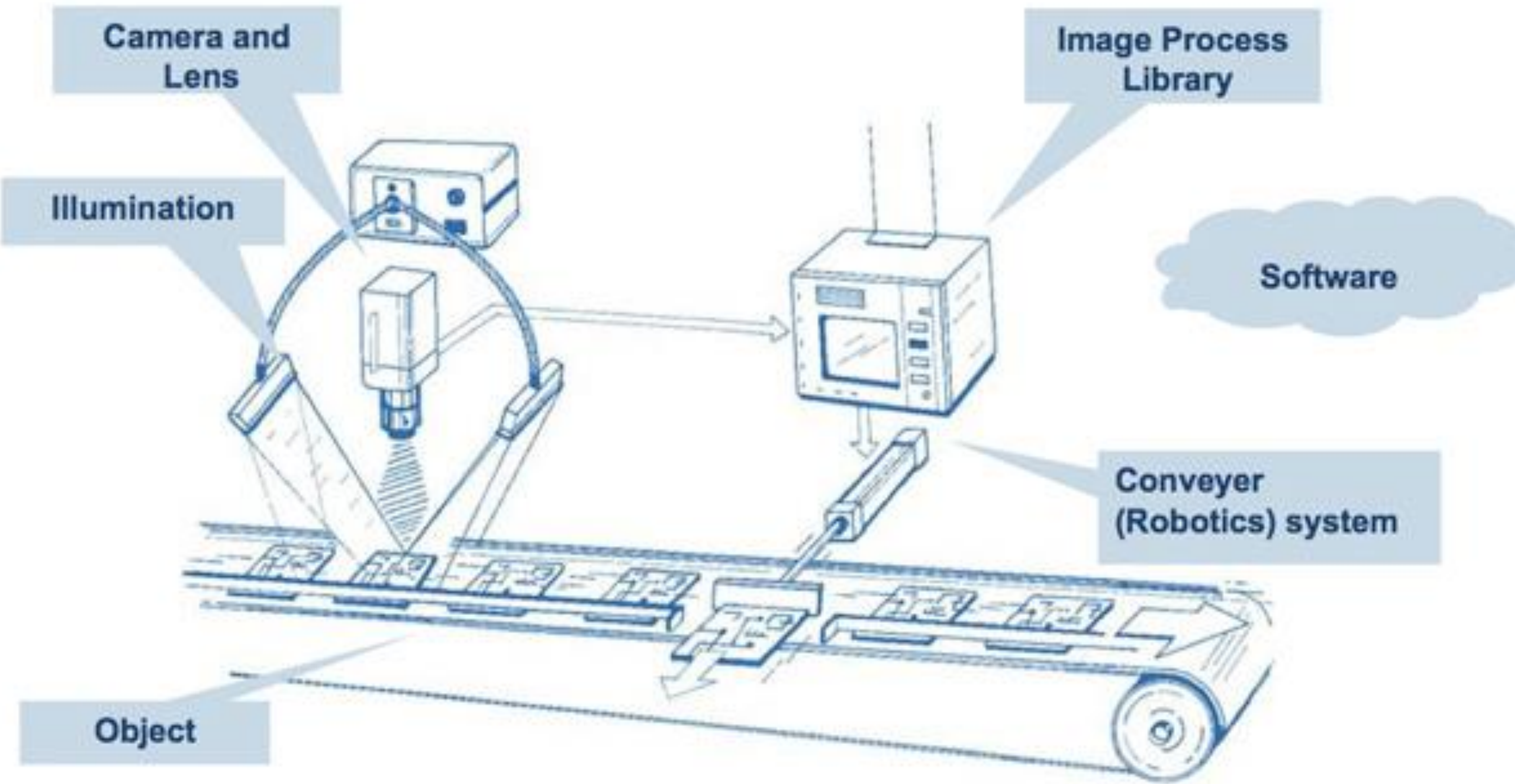
Conclude

Reference

Min 25-30 Research articles/ Books / Websites

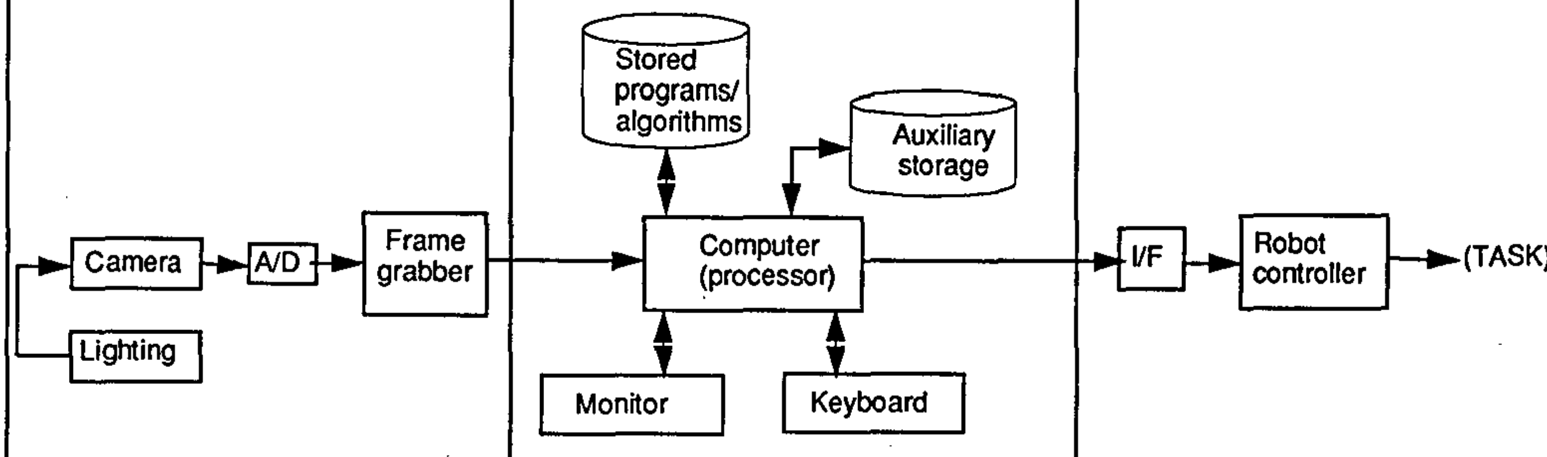
Last date for submission on 08.03.2021 (Monday)

Adaptive Control System



Adaptive Control System

HARDWARE



FUNCATION	I. SENSING AND DIGITIZING IMAGE DATA	II. IMAGE PROCESSING AND ANALYSIS	III. APPLICATIONS
TYPICAL TECHNIQUES AND APPLICATION	Signal conversion - Sampling - Quantization - Encoding Image storage/frame grabber Lighting - Structured light - Front/back lighting - Beam splitter - Retrore flectors - Specular illumination - Other techniques	Data reduction - Windowing - Digital conversion Segmentation - Thresholding - Region - Edge detection Feature extraction - Descriptors Object recognition - Template matching Other algorithms	Inspection Identification Visual servoing and navigation

Figure 2.16 Functions of a machine vision system [Groover et al 1986a]

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SCHOOL OF MECHANICAL ENGINEERING

DEPARTMENT OF MECHATRONICS ENGINEERING

UNIT – II - Adaptive Control System – SIC1612

SIC1612 - ADAPTIVE CONTROL SYSTEMS
UNIT - II

SATHYABAMA
INSTITUTE OF SCIENCE AND TECHNOLOGY
(DEEMED TO BE UNIVERSITY)

COURSE OBJECTIVES

- To make the student familiarize with adaptive control schemes and MRAS
- To identify the techniques of linear and nonlinear systems with unknown parameters
- To introduce stability robustness concepts with protection systems.

Adaptive Control System

UNIT 1 INTRODUCTION TO ADAPTIVE CONTROL SYSTEM **9 Hrs.**

Definition of adaptive control system - functions of adaptive control - Different approaches to Adaptive Control - gain scheduling - Relay feedback

UNIT 2 IDENTIFICATION OF ADAPTIVE CONTROL **9 Hrs.**

Conventional methods of Identifications - step response, impulse response, Bode plot - Identification of linear time-invariant systems - Adaptive observers - Sufficient richness condition for parameter convergence - Equation error and output error methods

UNIT 3 MODEL REFERENCE ADAPTIVE SYSTEMS (MRAS) **9 Hrs.**

The need for MRAS - An over view of adaptive control systems - Mathematical description of MRAS - Design hypothesis - Equivalent representation of MRAS.

UNIT 4 CLASSIFICATION OF ADAPTIVE CONTROL **9 Hrs.**

Definitions - Auto tuning - Types of adaptive control - Recent trends in self-tuning - Robustness studies - Multivariable systems - Model updating - General-purpose adaptive regulator

UNIT 5 ADAPTIVE PROTECTION **9 Hrs.**

Need of Adaptive Protection in the system - Techniques for adaptive strategies in distance protection - Synchro-phasor based adaptive protection schemes - protection schemes - SCADA based protection systems - FTA - Testing of Relays.

Max. 45 Hours

Adaptive Control System

TEXT / REFERENCE BOOKS

1. Astrom K.J, Wittenmark B, Adaptive Control, Addison-Wesley, 2nd edition, 1995
2. Shankar Sastry, Marc Bodson, "Adaptive Control", Prentice Hall of India (P) Ltd., 1993.
3. Chalam V.V "Adaptive Control Systems - Techniques & Applications" - Marcel Dekker Inc
4. Chang C. Hong, Tong H. Lee and Weng K. Ho, Adaptive Control, ISA press, Research Triangle Park, 1993.

END SEMESTER EXAM QUESTION PAPER PATTERN

Max. Marks : 100 **Exam Duration : 3 Hrs.**

PART A : 2 Questions from each unit, each carrying 2 marks **20 Marks**

PART B : 2 Questions from each unit with internal choice, each carrying 16 marks **80 Marks**

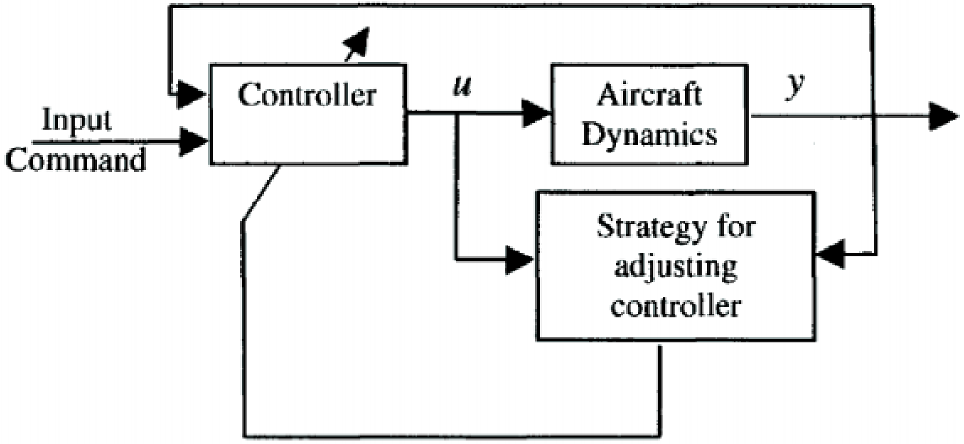
IDENTIFIER-BASED ADAPTIVE CONTROL

- 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.

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



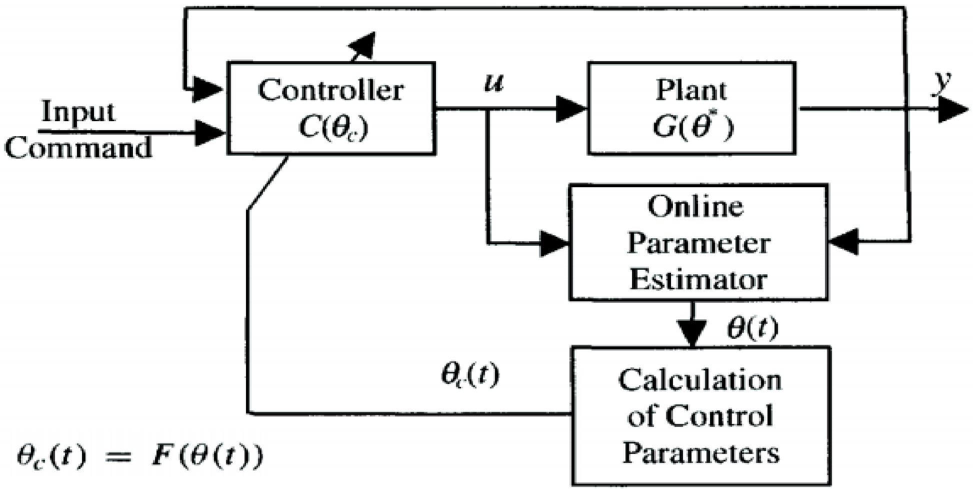
General adaptive control structure for aircraft control.

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



$$\theta_c(t) = F(\theta(t))$$

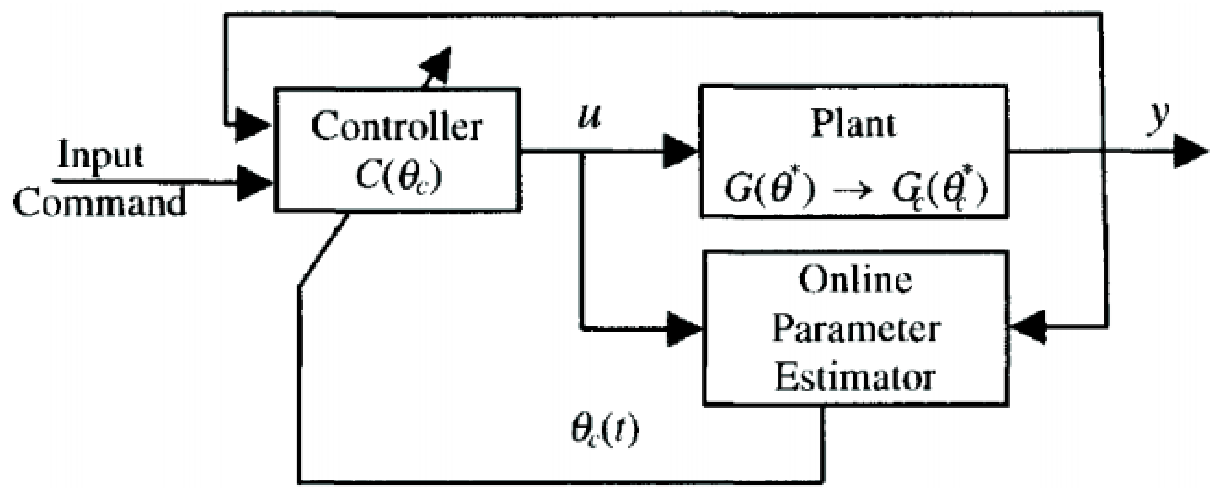
Indirect adaptive control structure.

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



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.

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 .

What is a Bode Plot

A Bode plot is a graph commonly used in control system engineering to determine the stability of a control system. A Bode plot maps the frequency response of the system through two graphs – the Bode magnitude plot (expressing the magnitude in decibels) and the Bode phase plot (expressing the phase shift in degrees).

Bode plots were first introduced in the 1930s by Hendrik Wade Bode while he was working at Bell Labs in the United States. Although Bode plots offer a relatively simple method to calculate system stability, they can not handle transfer functions with right half plane singularities (unlike Nyquist stability criterion).

Understanding **gain margins** and **phase margins** are crucial to understanding Bode plots.

Gain Margin

The greater the **Gain Margin** (GM), the greater the stability of the system. The gain margin refers to the amount of gain, which can be increased or decreased without making the system unstable. It is usually expressed as a magnitude in dB.

We can usually read the gain margin directly from the Bode plot (as shown in the diagram above). This is done by calculating the vertical distance between the magnitude curve (on the Bode magnitude plot) and the x-axis at the frequency where the Bode phase plot = 180°. This point is known as the **phase crossover frequency**.

It is important to realize that **the Gain and the Gain Margin are not the same things**. In fact, the Gain Margin is the negative of the gain (in decibels, dB). This will make sense when we look at the Gain margin formula.

Gain Margin Formula

The **formula for Gain Margin** (GM) can be expressed as:

$$GM = 0 - G\ dB$$

Where G is the gain. This is the magnitude (in dB) as read from the vertical axis of the magnitude plot at the phase crossover frequency.

In our example shown in the graph above, the Gain (G) is 20. Hence using our formula for gain margin, the gain margin is equal to 0 – 20 dB = -20 dB (unstable).

Phase Margin

The greater the **Phase Margin** (PM), the greater will be the stability of the system. The phase margin refers to the amount of phase, which can be increased or decreased without making the system unstable. It is usually expressed as a phase in degrees.

We can usually read the phase margin directly from the Bode plot (as shown in the diagram above). This is done by calculating the vertical distance between the phase curve (on the Bode phase plot) and the x-axis at the frequency where the Bode magnitude plot = 0 dB. This point is known as the **gain crossover frequency**.

It is important to realize that **the phase lag and the Phase Margin are not the same things**. This will make sense when we look at the phase margin formula.

Phase Margin Formula

The **formula for Phase Margin** (PM) can be expressed as:

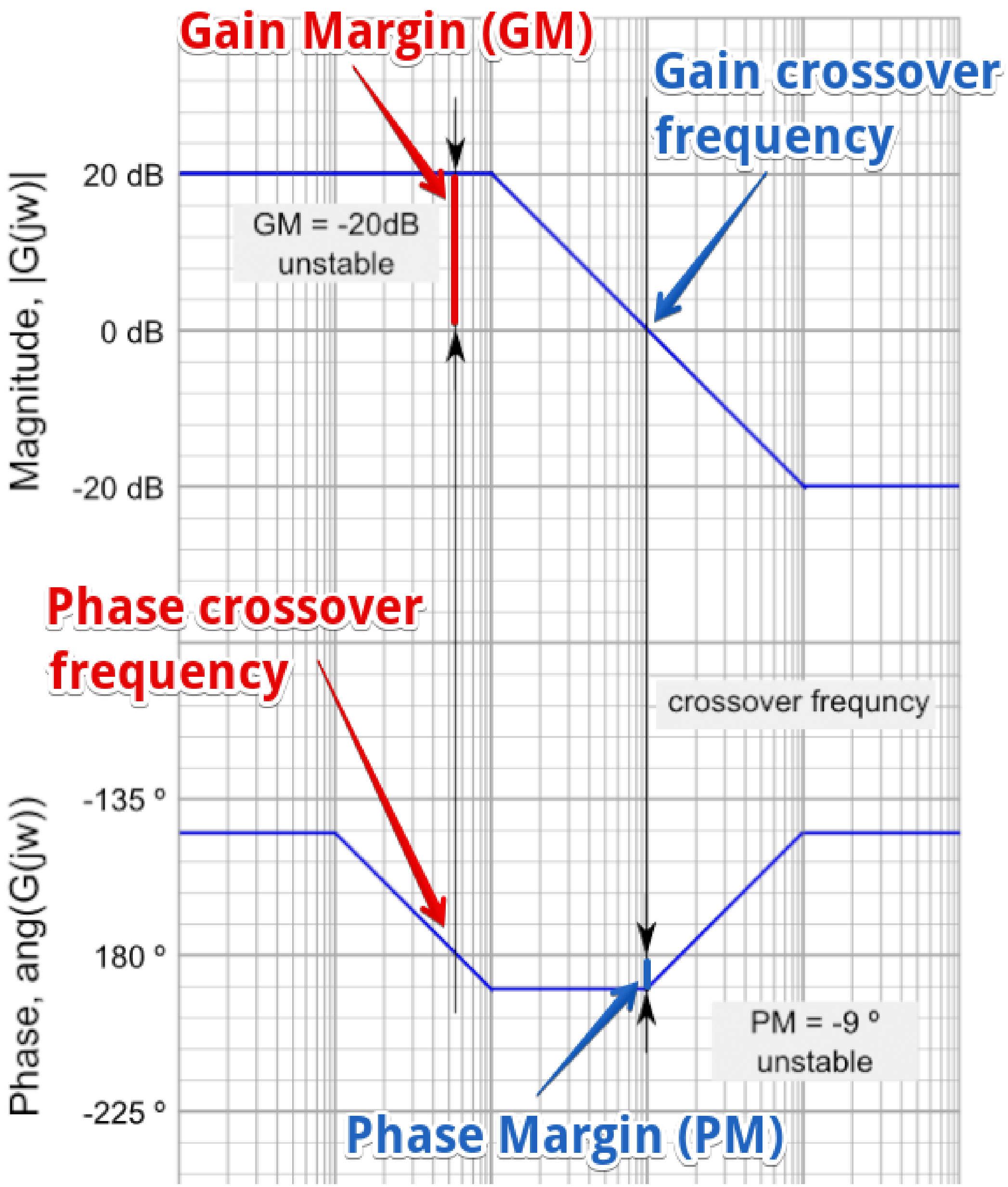
$$PM = \phi - (-180^\circ)$$

Where ϕ is the phase lag (a number less than 0). This is the phase as read from the vertical axis of the phase plot at the gain crossover frequency.

In our example shown in the graph above, the phase lag is -189°. Hence using our formula for phase margin, the phase margin is equal to -189° – (-180°) = -9° (unstable).

As another example, if an amplifier's open-loop gain crosses 0 dB at a frequency where the phase lag is -120°, then the phase lag -120°. Hence the phase margin of this feedback system is -120° – (-180°) = 60° (stable).

Adaptive Control System



Bode Plot Stability

Below is a summarized list of criterion relevant to drawing Bode plots (and calculating their stability):

1. Gain Margin: Greater will the **gain margin** greater will be the stability of the system. It refers to the amount of gain, which can be increased or decreased without making the system unstable. It is usually expressed in dB.
2. Phase Margin: Greater will the **phase margin** greater will be the stability of the system. It refers to the phase which can be increased or decreased without making the system unstable. It is usually expressed in phase.
3. Gain Crossover Frequency: It refers to the frequency at which the magnitude curve cuts the zero dB axis in the bode plot.
4. Phase Crossover Frequency: It refers to the frequency at which phase curve cuts the negative times the 180o axis in this plot.
5. Corner Frequency: The frequency at which the two asymptotes cuts or meet each other is known as break frequency or corner frequency.
6. Resonant Frequency: The value of frequency at which the modulus of G (jω) has a peak value is known as the resonant frequency.
7. Factors: Every loop transfer function {i.e. G(s) × H(s)} product of various factors like constant term K, Integral factors (jω), first-order factors (1 + jωT)(± n) where n is an integer, second-order or quadratic factors.
8. Slope: There is a slope corresponding to each factor and slope for each factor is expressed in the dB per decade.
9. Angle: There is an angle corresponding to each factor and angle for each factor is expressed in the degrees.

Adaptive Control System

Now there are some results that one should remember in order to plot the Bode curve. These results are written below:

- Constant term K: This factor has a slope of zero dB per decade. There is no corner frequency corresponding to this constant term. The phase angle associated with this constant term is also zero.
- Integral factor $1/(j\omega)^n$: This factor has a slope of $-20 \times n$ (where n is an integer)dB per decade. There is no corner frequency corresponding to this integral factor. The phase angle associated with this integral factor is $-90 \times n$. Here n is also an integer.
- First order factor $1/(1+j\omega T)$: This factor has a slope of -20 dB per decade. The corner frequency corresponding to this factor is 1/T radian per second. The phase angle associated with this first factor is $-\tan^{-1}(\omega T)$.
- First order factor $(1+j\omega T)$: This factor has a slope of 20 dB per decade. The corner frequency corresponding to this factor is 1/T radian per second. The phase angle associated with this first factor is $\tan^{-1}(\omega T)$.
- Second order or quadratic factor : $[\{1/(1+(2\zeta/\omega)\} \times (j\omega) + \{(1/\omega^2)\} \times (j\omega)^2)]$: This factor has a slope of -40 dB per decade. The corner frequency corresponding to this factor is ω^n radian per second. The phase angle associated with this first factor is

$$tan^{-1}\left\{\frac{\frac{2\zeta\omega}{\omega n}}{1-\left(\frac{\omega}{\omega n}\right)^2}\right\}$$

How to Draw Bode Plot

Keeping all the above points in mind, we are able to draw a Bode plot for any kind of control system. Now let us discuss the procedure of drawing a Bode plot:

1. Substitute the $s = j\omega$ in the open loop transfer function $G(s) \times H(s)$.
2. Find the corresponding corner frequencies and tabulate them.
3. Now we are required one semi-log graph chooses a frequency range such that the plot should start with the frequency which is lower than the lowest corner frequency. Mark angular frequencies on the x-axis, mark slopes on the left hand side of the y-axis by marking a zero slope in the middle and on the right hand side mark phase angle by taking -180° in the middle.
4. Calculate the gain factor and the type of order of the system.
5. Now calculate slope corresponding to each factor.

Adaptive Control System

<u>For drawing the **Bode magnitude plot**</u>:

- Mark the corner frequency on the semi-log graph paper.
- Tabulate these factors moving from top to bottom in the given sequence.
  1. Constant term K.
  2. Integral factor
     $$\frac{1}{j\omega^n}$$
  3. First order factor
     $$\frac{1}{1+j\omega T}$$
  4. First order factor (1+jωT).
  5. Second order or quadratic factor:
     $$\left[\frac{1}{1+(2\zeta/\omega)}\times(j\omega)+\left(\frac{1}{\omega^2}\right)\times(j\omega)^2\right]$$
- Now sketch the line with the help of the corresponding slope of the given factor. Change the slope at every corner frequency by adding the slope of the next factor. You will get the magnitude plot.
- Calculate the gain margin.

<u>For drawing the **Bode phase plot**</u>:

1. Calculate the phase function adding all the phases of factors.
2. Substitute various values to the above function in order to find out the phase at different points and plot a curve. You will get a phase curve.
3. Calculate the phase margin.

Bode Stability Criterion

Stability conditions are given below:

1. For a Stable System: Both the margins should be positive or phase margin should be greater than the gain margin.
2. For Marginal Stable System: Both the margins should be zero or phase margin should be equal to the gain margin.
3. For Unstable System: If any of them is negative or **phase margin** should be less than the gain margin.

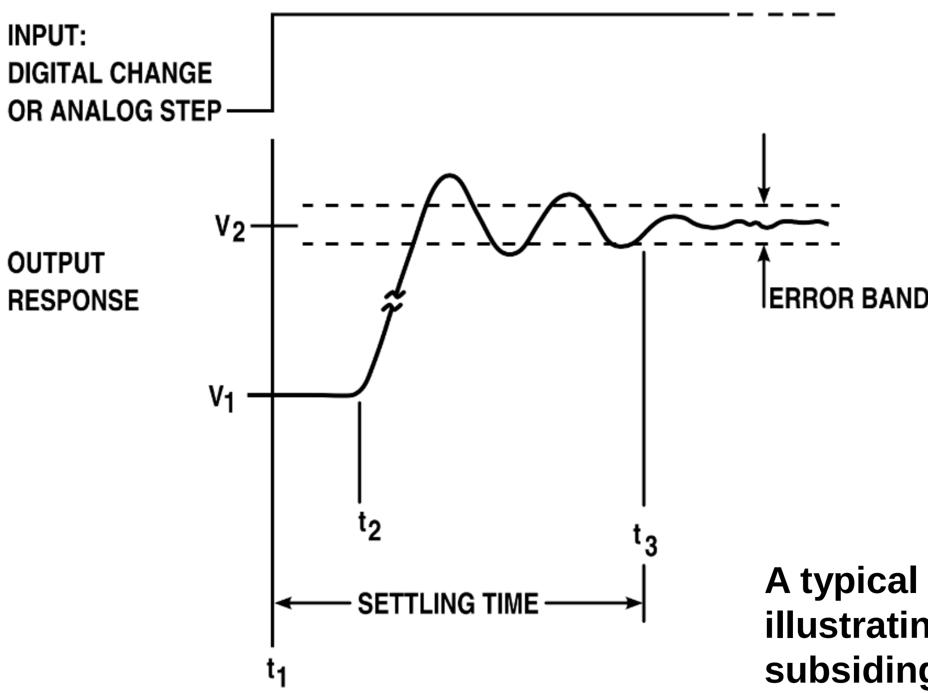
Advantages of a Bode Plot

1. It is based on the asymptotic approximation, which provides a simple method to plot the logarithmic magnitude curve.
2. The multiplication of various magnitude appears in the transfer function can be treated as an addition, while division can be treated as subtraction as we are using a logarithmic scale.
3. With the help of this plot only we can directly comment on the stability of the system without doing any calculations.
4. **Bode plots** provide relative stability in terms of **gain margin** and **phase margin**.
5. It also covers from low frequency to high frequency range.

STEP RESPONSE

The step response of a system in a given initial state consists of the time evolution of its outputs when its control inputs are Heaviside step functions. In electronic engineering and control theory, step response is the time behaviour of the outputs of a general system when its inputs change from zero to one in a very short time. The concept can be extended to the abstract mathematical notion of a dynamical system using an evolution parameter.

From a practical standpoint, knowing how the system responds to a sudden input is important because large and possibly fast deviations from the long term steady state may have extreme effects on the component itself and on other portions of the overall system dependent on this component. In addition, the overall system cannot act until the component's output settles down to some vicinity of its final state, delaying the overall system response. Formally, knowing the step response of a dynamical system gives information on the stability of such a system, and on its ability to reach one stationary state when starting from another.



A typical step response for a second order system, illustrating overshoot, followed by ringing, all subsiding within a settling time.

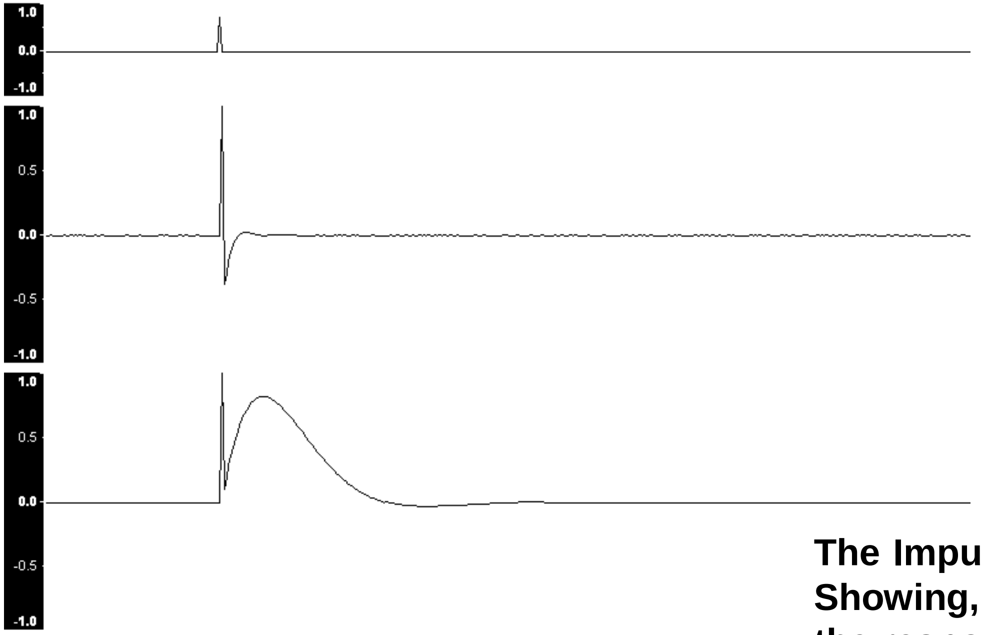
IMPULSE RESPONSE

In signal processing, the **impulse response**, or **impulse response function (IRF)**, of a dynamic system is its output when presented with a brief input signal, called an impulse.

More generally, an impulse response is the reaction of any dynamic system in response to some external change. In both cases, the impulse response describes the reaction of the system as a function of time (or possibly as a function of some other independent variable that parameterizes the dynamic behavior of the system).

In all these cases, the dynamic system and its impulse response may be actual physical objects, or may be mathematical systems of equations describing such objects.

Since the impulse function contains all frequencies, the impulse response defines the response of a linear time-invariant system for all frequencies.

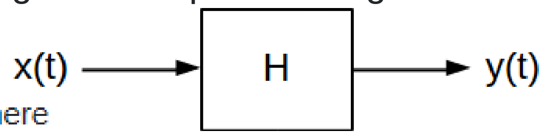


The Impulse response from a simple audio system. Showing, from top to bottom, the original impulse, the response after high frequency boosting, and the response after low frequency boosting.

Adaptive Control System

The impulse response and frequency response are two attributes that are useful for characterizing linear time-invariant (LTI) systems. They provide two different ways of calculating what an LTI system's output will be for a given input signal. A continuous-time LTI system is usually illustrated like this:

In general, the system HH maps its input signal x(t)x(t) to a corresponding output signal y(t)y(t). There are many types of LTI systems that can have apply very different transformations to the signals that pass through them. But, they all share two key characteristics:



In general, the system H maps its input signal $x(t)$ to a corresponding output signal $y(t)$. There are many types of LTI systems that can have apply very different transformations to the signals that pass through them. But, they all share two key characteristics:

- The system is *linear*, so it obeys the principle of superposition. Stated simply, if you linearly combine two signals and input them to the system, the output is the same linear combination of what the outputs would have been had the signals been passed through individually. That is, if $x_1(t)$ maps to an output of $y_1(t)$ and $x_2(t)$ maps to an output of $y_2(t)$, then for all values of a_1 and a_2,

$$H\{a_1x_1(t) + a_2x_2(t)\} = a_1y_1(t) + a_2y_2(t)$$

- The system is *time-invariant*, so its characteristics do not change with time. If you add a delay to the input signal, then you simply add the same delay to the output. For an input signal $x(t)$ that maps to an output signal $y(t)$, then for all values of τ,

$$H\{x(t-\tau)\} = y(t-\tau)$$

Discrete-time LTI systems have the same properties; the notation is different because of the discrete-versus-continuous difference, but they are a lot alike. These characteristics allow the operation of the system to be straightforwardly characterized using its impulse and frequency responses. They provide two perspectives on the system that can be used in different contexts.

LINEAR TIME-INVARIANT SYSTEMS (LTI SYSTEMS)

Linear time-invariant systems (LTI systems) are a class of systems used in signals and systems that are both linear and time-invariant.

Linear systems are systems whose outputs for a linear combination of inputs are the same as a linear combination of individual responses to those inputs.

Time-invariant systems are systems where the output does not depend on *when* an input was applied. These properties make LTI systems easy to represent and understand graphically.

LTI systems are superior to simple state machines for representation because they have more memory.

LTI systems, unlike state machines, have a memory of past states and have the ability to predict the future.

LTI systems are used to predict long-term behavior in a system. So, they are often used to model systems like power plants.

Another important application of LTI systems is electrical circuits. These circuits, made up of inductors, transistors, and resistors, are the basis upon which modern technology is built.

https://brilliant.org/wiki/linear-time-invariant-systems/

Properties of LTI Systems

LTI systems are those that are both linear and time-invariant.

Linear systems have the property that the output is linearly related to the input. Changing the input in a linear way will change the output in the same linear way. So if the input $x_1(t)$ produces the output $y_1(t)$ and the input $x_2(t)$ produces the output $y_2(t)$, then linear combinations of those inputs will produce linear combinations of those outputs. The input $\left(x_1(t)+x_2(t)\right)$ will produce the output $\left(y_1(t)+y_2(t)\right)$. Further, the input $\left(a_1 \cdot x_1(t)+a_2 \cdot x_2(t)\right)$ will produce the output $(a_1 \cdot y_1(t)+a_2 \cdot y_2(t))$ for some constants a_1 and a_2.

In other words, for a system T over time t, composed of signals $x_1(t)$ and $x_2(t)$ with outputs $y_1(t)$ and $y_2(t)$,

$$T\left[a_1 x_1(t)+a_2 x_2(t)\right]=a_1 T\left[x_1(t)\right]+a_2 T\left[x_2(t)\right]=a_1 y_1(t)+a_2 y_2(t),$$

where a_1 and a_2 are constants.

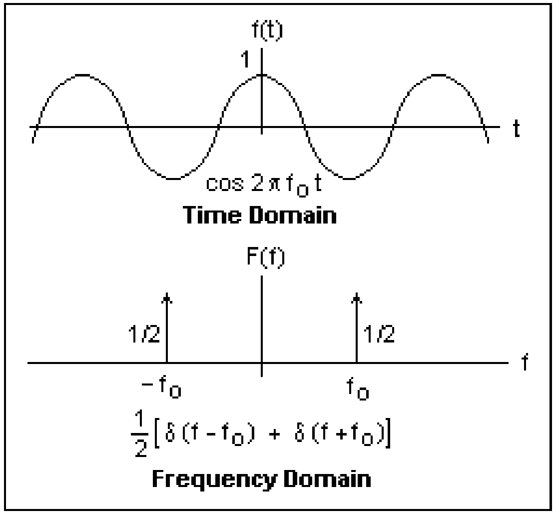
Further, the output of a linear system for an input of 0 is also 0.

Time-invariant systems are systems where the output for a particular input does not change depending on when that input was applied. A time-invariant systems that takes in signal $x(t)$ and produces output $y(t)$ will also, when excited by signal $x(t+\sigma)$, produce the time-shifted output $y(t+\sigma)$.

Thus, the entirety of an LTI system can be described by a single function called its **impulse response**. This function exists in the time domain of the system. For an arbitrary input, the output of an LTI system is the convolution of the input signal with the system's impulse response.

Conversely, the LTI system can also be described by its **transfer function**. The transfer function is the Laplace transform of the impulse response. This transformation changes the function from the time domain to the frequency domain. This transformation is important because it turns differential equations into algebraic equations, and turns convolution into multiplication. In the frequency domain, the output is the product of the transfer function with the transformed input. The shift from time to frequency is illustrated in the following image:

Adaptive Control System



In addition to linear and time-invariant, LTI systems are also memory systems, invertible, casual, real, and stable. That means they have memory, they can be inverted, they depend only on current and past events, they have fully real inputs and outputs, and they produce bounded output for bounded input.

Because of the properties of LTI systems, the general form of an LTI system with output $y[n]$ and input $x[n]$ at time n, and constants c_k and d_j is defined a

$$y[n] = c_0 y[n-1] + c_1 y[n-2] + \ldots + c_{k-1} y[n-k] + d_0 x[n] + d_1 x[n-1] + \ldots + d_j x[n-j].$$

The state of this system depends on the previous k output values and j input values. Because of the linearity property, the output at time n is just a linear combination of the previous outputs, previous inputs, and current input.

Further, if a string of LTI systems are cascaded together, the output of that new system does not depend on the order in which the systems were cascaded. This property follows from the associative property and the commutative property.

Adaptive Control System

We can take the general form of the LTI system, and write it as an operator equation, and with some manipulation we can turn it into a useful formula:

$$\begin{aligned} Y &= c_0\mathcal{R}Y + c_1\mathcal{R}^2Y + \cdots + c_{k-1}\mathcal{R}^kY + d_0X + d_1\mathcal{R}X + \cdots + d_j\mathcal{R}^jX \\ &= Y\left(c_0\mathcal{R} + c_1\mathcal{R}^2 + \cdots + c_{k-1}\mathcal{R}^k\right) + X\left(d_0 + d_1\mathcal{R} + \cdots + d_j\mathcal{R}^j\right). \end{aligned}$$

This is the same equation as

$$Y\left(1 - c_0\mathcal{R} - c_1\mathcal{R}^2 - \ldots - c_{k-1}\mathcal{R}^k\right) = X\left(d_0 + d_1\mathcal{R} + \cdots + d_j\mathcal{R}^j\right).$$

We can then do some division to create an equation that describes the quotient of the output signal and the input signal:

$$\frac{Y}{X} = \frac{d_0 + d_1\mathcal{R} + \cdots + d_j\mathcal{R}^j}{1 - c_0\mathcal{R} - c_1\mathcal{R}^2 - \ldots - c_{k-1}\mathcal{R}^k}.$$

This is the **system function** of the LTI system, and it is typically written as the polynomial

$$\frac{Y}{X} = \frac{b_0 + b_1\mathcal{R} + b_2\mathcal{R}^2 + \cdots}{a_0 + a_1\mathcal{R} + a_2\mathcal{R}^2 + \cdots}.$$

Note that both the numerator and the denominator are polynomials in $\mathcal{R}$, the delay variable. Understanding the different roles that the numerator and denominator play is important.

Adaptive Control System

The Impulse Response

The impulse response is an especially important property of any LTI system. We can use it to describe an LTI system and predict its output for any input. To understand the impulse response, we need to use the **unit impulse signal**, one of the signals described in the Signals and Systems wiki. It has many important applications in sampling. The unit impulse signal is simply a signal that produces a signal of 1 at time = 0. It is zero everywhere else. With that in mind, an LTI system's impulse function is defined as follows:

DEFINITION

The impulse response for an LTI system is the output, $y(t)$, when the input is the unit impulse signal, $\sigma(t)$. In other words,

$$\text{when } x(t) = \sigma(t), \;\; h(t) = y(t).$$

Essentially, the impulse function for an LTI system basically asks this: If we introduce a unit impulse signal at a certain time, what will be the output of the system at a later time? Sometimes, we can even find the impulse response by doing just that: introducing an impulse signal and seeing what happens.

Convolution

Convolution is a representation of signals as a linear combination of delayed input signals. In other words, we're just breaking down a signal into the inputs that were used to create it. However, it is used differently between discrete time signals and continuous time signals because of their underlying properties. Discrete time signals are simply linear combinations of discrete impulses, so they can be represented using the **convolution sum**. Continuous signals, on the other hand, are continuous. Much like calculating the area under the curve of a continuous function, these signals require the **convolution integral**.

Convolution Sum

$$y[n] = \sum_{k=-\infty}^{\infty} x[k]\, h[n-k]$$

Convolution Integral

$$y(t) = \int_{-\infty}^{\infty} h(\tau)x(t-\tau)\, d\tau = x(t) * h(t)$$

Convolution has many important properties:

1. Commutativity: $x(t) * h(t) = h(t) * x(t)$
2. Associativity: $[x(t) * h_1(t)] * h_2(t) = x(t) * [h_1(t) * h_2(t)]$
3. Distributivity of Addition: $x(t) * [h_1(t) + h_2(t)] = x(t) * h_1(t) + x(t) * h_2(t)$
4. Identity Element: $x(t) * h(t) = h(t)$

Note: $*$ is the mathematical convolution symbol.

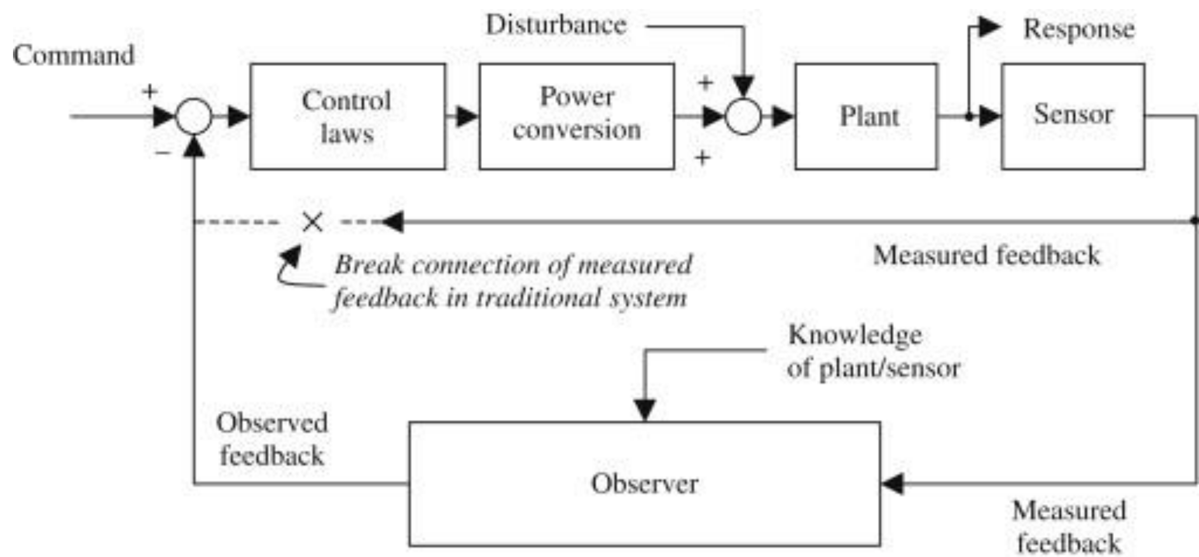
All LTI systems can be described using this integral or sum, for a suitable function $h()$. $h()$ is the impulse function for the signal. The output of any LTI system can be calculated using the input and the impulse function for that system.

ADAPTIVE OBSERVERS

An adaptive observer is an algorithm for recursive joint estimation of state and parameters of a dynamic system or for state estimation only despite the presence of unknown parameters

Such algorithms have important applications in fault detection and isolation (FDI) and in adaptive control

Adaptive observers are used to estimate system states and parameters, simultaneously



If the persistency excitation condition is satisfied, the parameter estimation error converges to zero. The stability of the adaptive observers is generally provided by In recent years, the theory of adaptive observers are extended to estimate unknown inputs, nonlinear systems and fault detection.

Consider the LTI SISO plant

$$\begin{aligned} \dot{x} &= Ax + Bu, \qquad x(0) = x_0 \\ y &= C^\top x \end{aligned} \tag{5.3.1}$$

where $x \in \mathcal{R}^n$. We assume that u is a piecewise continuous and bounded function of time, and A is a stable matrix. In addition we assume that the plant is completely controllable and completely observable.

The problem is to construct a scheme that estimates both the parameters of the plant, i.e., A, B, C as well as the state vector x using only I/O measurements. We refer to such a scheme as the *adaptive observer*.

A good starting point for choosing the structure of the adaptive observer is the state observer, known as the Luenberger observer, used to estimate the state vector x of the plant (5.3.1) when the parameters A, B, C are known.

5.3.1 The Luenberger Observer

If the initial state vector x_0 is known, the estimate $\hat{x}$ of x in (5.3.1) may be generated by the state observer

$$\dot{\hat{x}} = A\hat{x} + Bu, \quad \hat{x}(0) = x_0 \tag{5.3.2}$$

where $\hat{x} \in \mathcal{R}^n$. Equations (5.3.1) and (5.3.2) imply that $\hat{x}(t) = x(t), \forall t \geq 0$. When x_0 is unknown and A is a stable matrix, the following state observer may be used to generate the estimate $\hat{x}$ of x:

$$\dot{\hat{x}} = A\hat{x} + Bu, \quad \hat{x}(0) = \hat{x}_0 \tag{5.3.3}$$

In this case, the state observation error $\tilde{x} = x - \hat{x}$ satisfies the equation

$$\dot{\tilde{x}} = A\tilde{x}, \qquad \tilde{x}(0) = x_0 - \hat{x}_0$$

which implies that $\tilde{x}(t) = e^{At}\tilde{x}(0)$. Because A is a stable matrix $\tilde{x}(t) \to 0$, i.e., $\hat{x}(t) \to x(t)$ as $t \to \infty$ exponentially fast with a rate that depends on the location of the eigenvalues of A. The observers (5.3.2), (5.3.3) contain no feedback terms and are often referred to as *open-loop observers*.

When x_0 is unknown and A is not a stable matrix, or A is stable but the state observation error is required to converge to zero faster than the rate with which $\| e^{At} \|$ goes to zero, the following observer, known as the *Luenberger observer*, is used:

$$\begin{aligned} \dot{\hat{x}} &= A\hat{x} + Bu + K(y - \hat{y}), \quad \hat{x}(0) = \hat{x}_0 \\ \hat{y} &= C^\top \hat{x} \end{aligned} \tag{5.3.4}$$

where K is a matrix to be chosen by the designer. In contrast to (5.3.2) and (5.3.3), the Luenberger observer (5.3.4) has a feedback term that depends on the output observation error $\tilde{y} = y - \hat{y}$.

The state observation error $\tilde{x} = x - \hat{x}$ for (5.3.4) satisfies

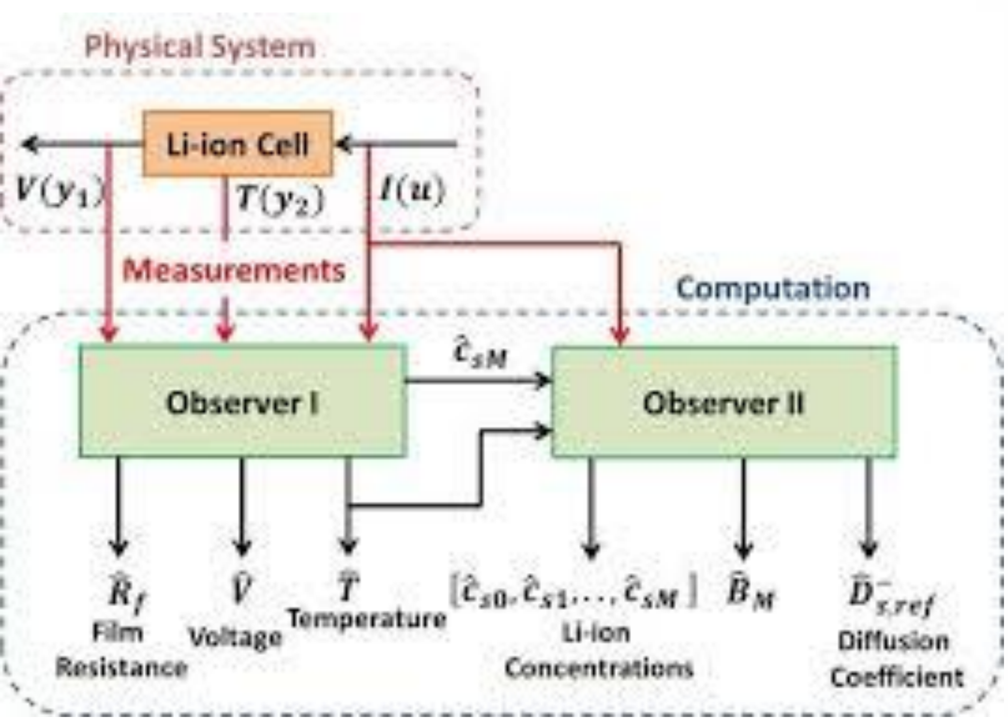
$$\dot{\tilde{x}} = (A - KC^\top)\tilde{x}, \qquad \tilde{x}(0) = x_0 - \hat{x}_0 \tag{5.3.5}$$

Because (C, A) is an observable pair, we can choose K so that $A - KC^\top$ is a stable matrix. In fact, the eigenvalues of $A - KC^\top$, and, therefore, the rate of convergence of $\tilde{x}(t)$ to zero can be arbitrarily chosen by designing K appropriately [95]. Therefore, it follows from (5.3.5) that $\hat{x}(t) \to x(t)$ exponentially fast as $t \to \infty$, with a rate that depends on the matrix $A - KC^\top$. This result is valid for any matrix A and any initial condition x_0 as long as (C, A) is an observable pair and A, C are known.

Adaptive Control System

These observers have been studied since the early 1970s. The cornerstone of these adaptive observers is to build a Luenberger observer with parameters that can be updated in real time.

State observer or state estimator is a system that provides an estimate of the internal state of a given real system, from measurements of the input and output of the real system. It is typically computer-implemented, and provides the basis of many practical applications.



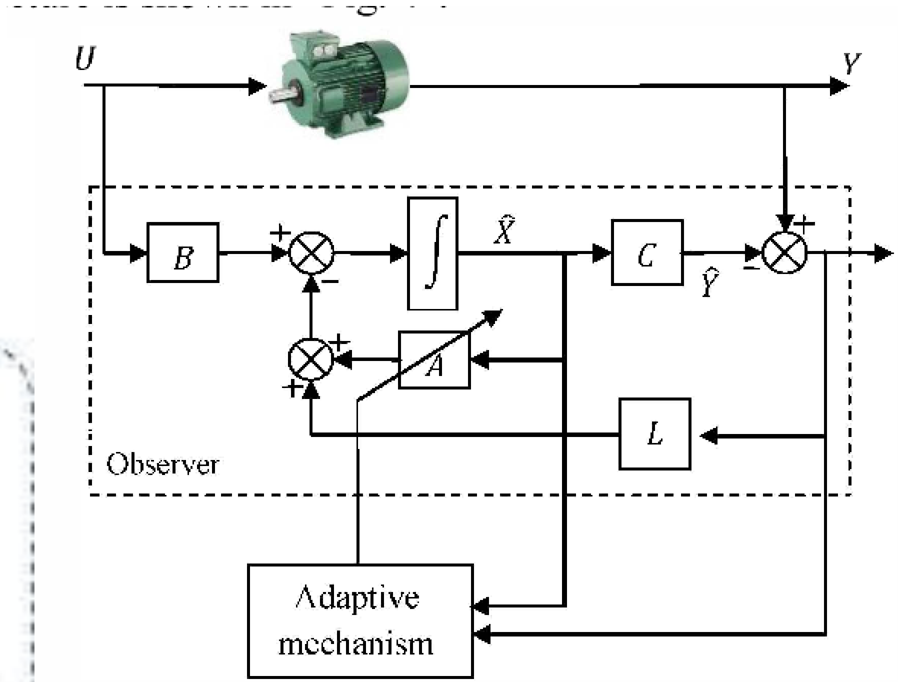
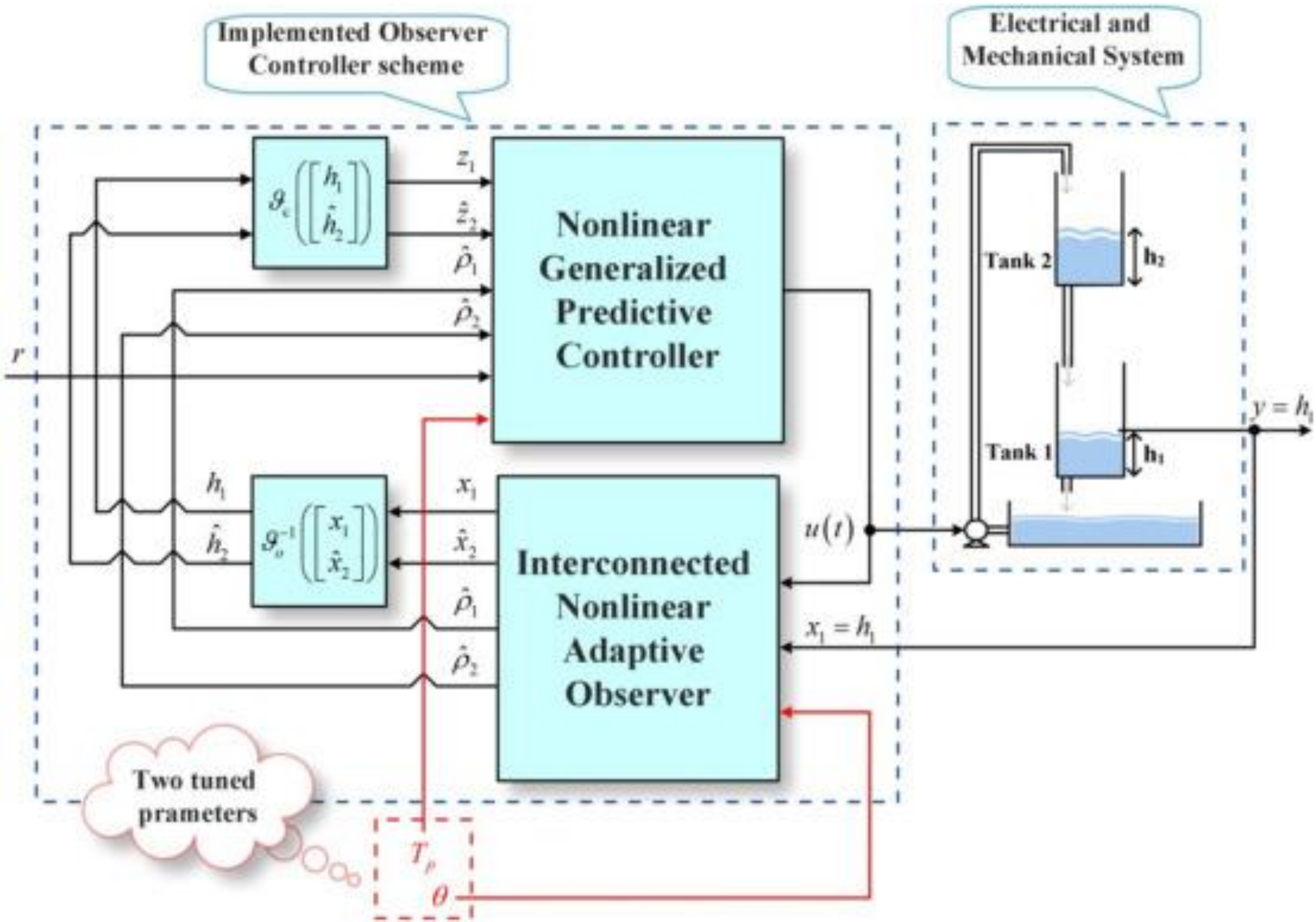
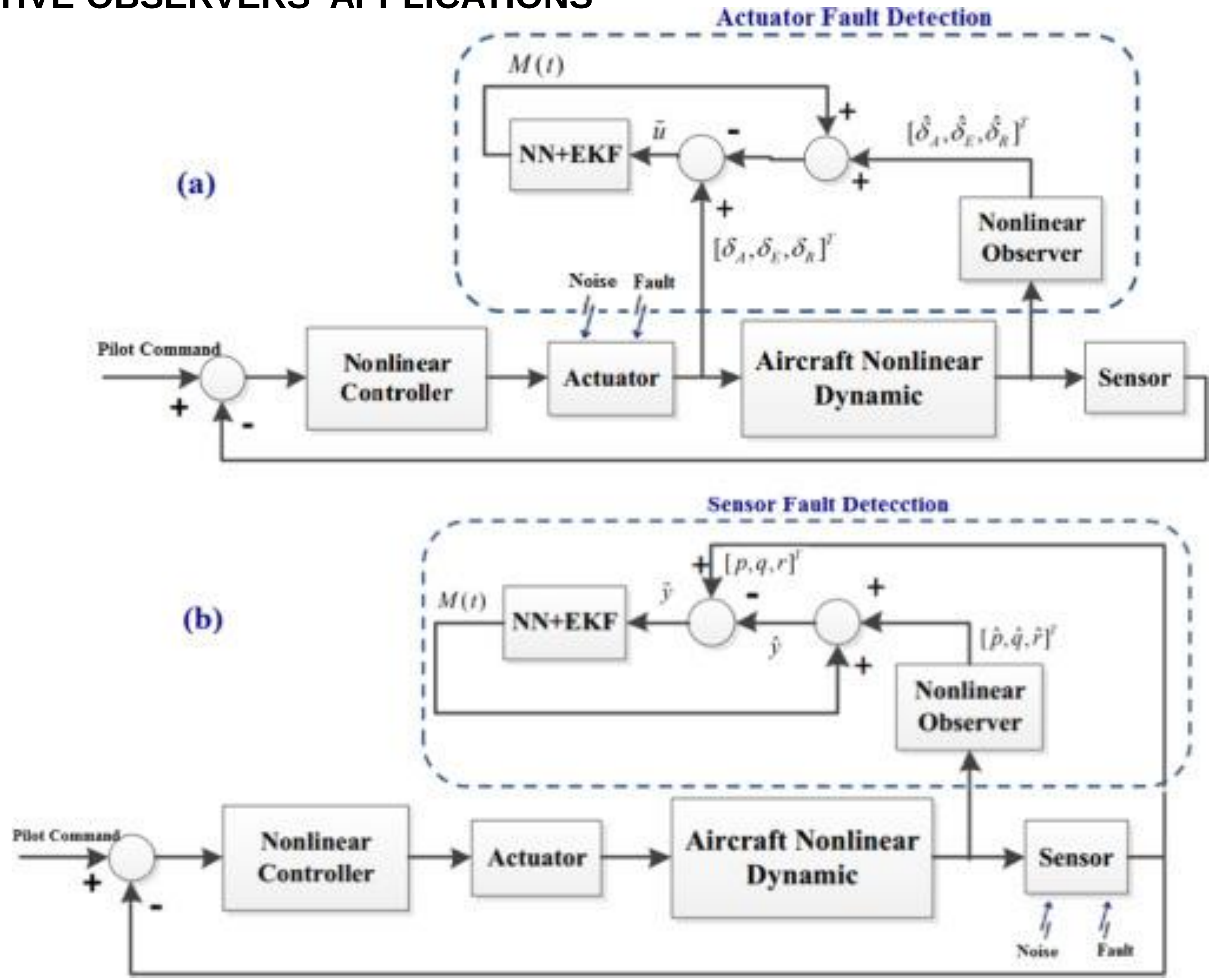


Figure 4. Structure of the adaptive Luenberger observer

ADAPTIVE OBSERVERS APPLICATIONS



ADAPTIVE OBSERVERS APPLICATIONS



The design of an adaptive observer is based on the combination of a state observer that could be used to estimate the state variables of a particular plant state-space representation with an on-line estimation scheme.

The choice of the plant state-space representation is crucial for the design and stability analysis of the adaptive observer.

The stability properties of the adaptive observers developed are based on the assumption that the plant is stable and the plant input is bounded.

Sufficient richness condition for parameter convergence – Assignment Topic

Equation error and output error methods

Why Use Error Identification & Analysis?

Human error introduces a large number of problems into a system. Reducing the amount of errors that occur through changes in design can improve efficiency, safety, usability, and user satisfaction. In some situations, the number or criticality of errors is so great that the tasks the system was designed to achieve become impossible. Error reduction (or ideally elimination) is obviously more important in some domains than others. Safety critical domains like nuclear and medical fields have a greater focus on human error than entertainment software.

Equation error and output error methods

When Use Error Identification & Analysis?

Error can be assessed at multiple points in the design cycle. Early on, when conducting a task analysis, designers may predict points of error and try to eliminate them through their initial designs. Inevitably, not all error will be predictable, and more errors will be found during the user testing stage. Ideally a design will be iterated numerous times and the number of errors will drop with each design. However, it is always possible that a change in the design that improves some aspects of usability ends up generating new errors.

Equation error and output error methods

How to Identify and Analyze Errors?

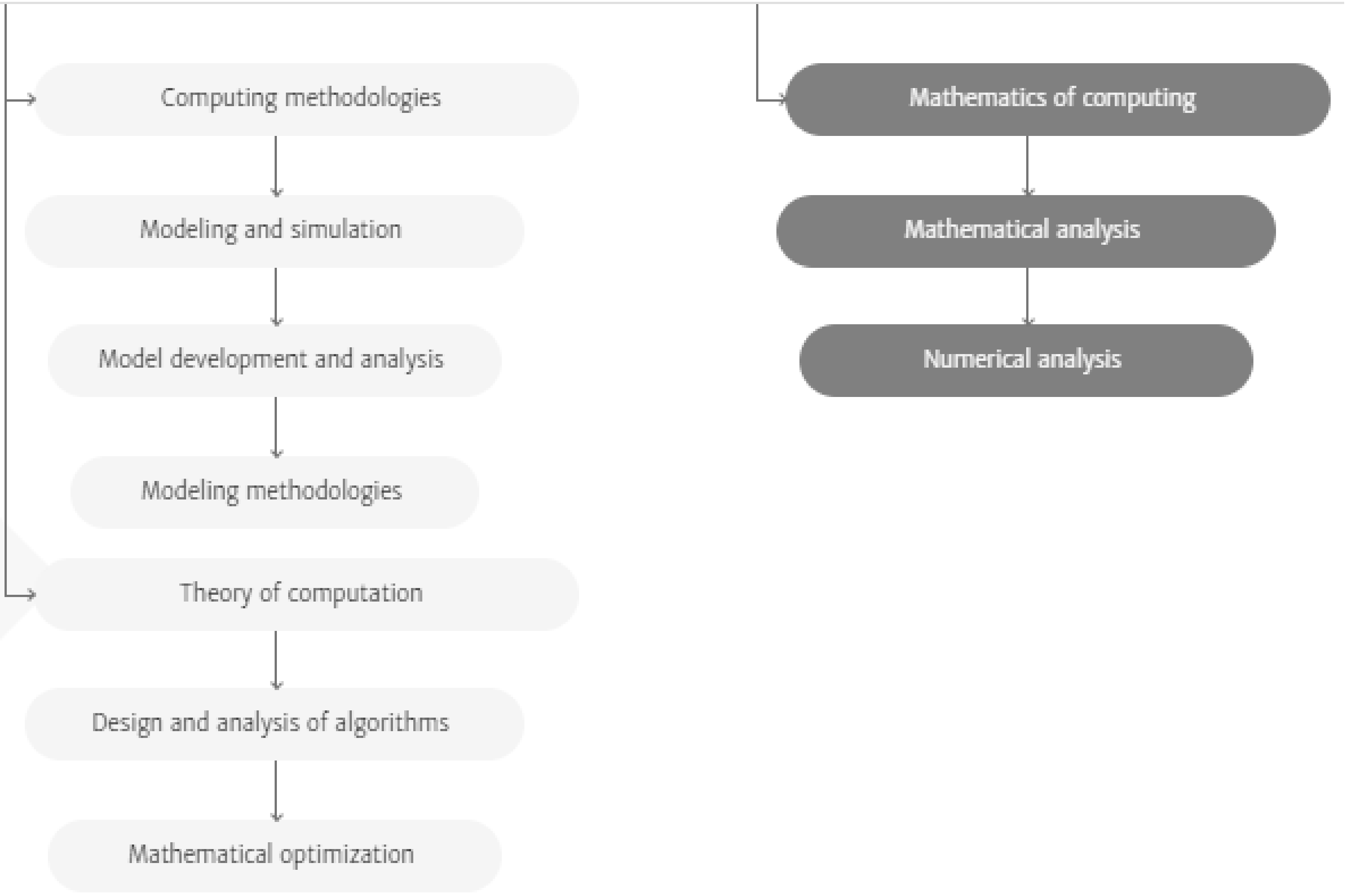
There are a tremendous number of ways to identify and analyze errors. Everyone seems to want to create their own system and develop an acronym to refer to it. Human factors professionals will likely find a way that works best for them.

Many error identification systems tie errors to the process of task analysis (often hierarchical task analysis), analyzing errors at every step of the task. Errors are sometimes classified based on type, as this can assist with removing the error from the system. Some error identification systems have been developed for specific domains, such as nuclear power.

Equation error and output error methods

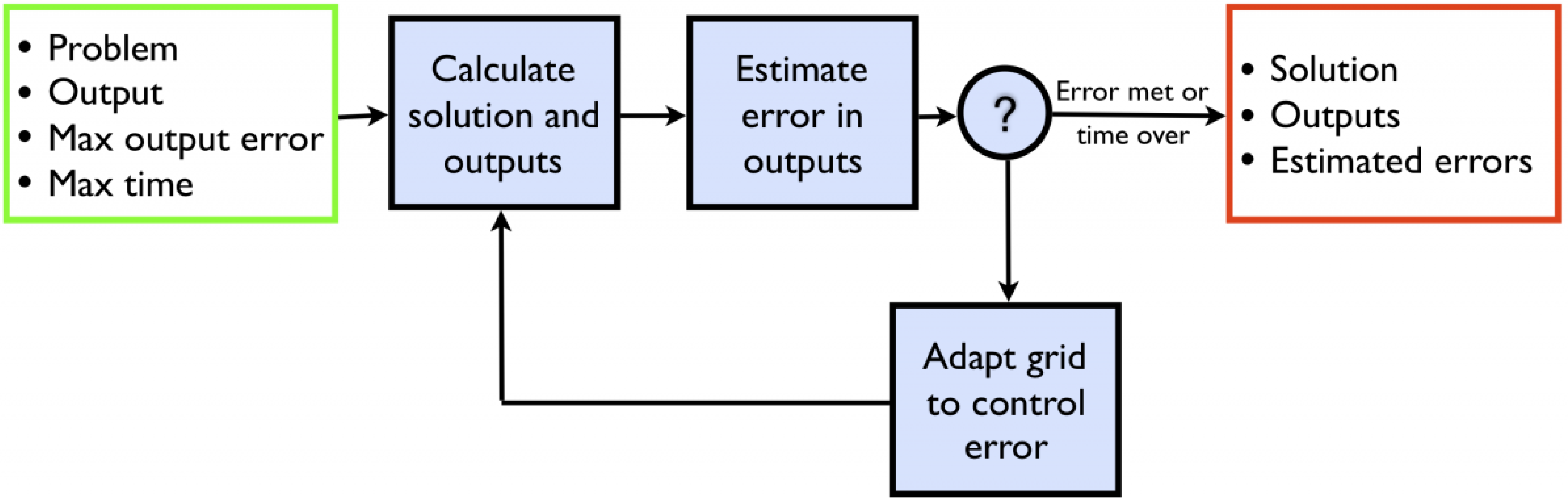
An equation error method is developed which trans- forms the inverse problem into a system of linear operator equations for the diffusion coefficient and which can be solved by the conjugate gradient method in a very efficient and stable manner.

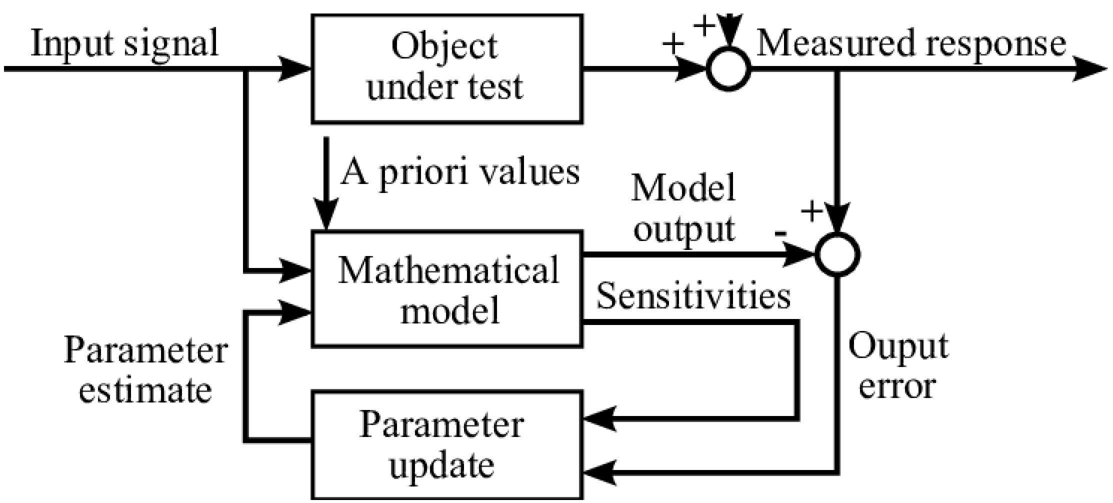
Equation error method and output error method in identification of continuous systems



Adaptive Control System

The output error identification method is studied in various respects. The stationary points of the associated loss function are investigated. Sufficient conditions for a unique local minimum are given. The loss functions can be minimized using a quasilinearization algorithm.





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SCHOOL OF MECHANICAL ENGINEERING

DEPARTMENT OF MECHATRONICS ENGINEERING

UNIT – III - Adaptive Control System – SIC1612

SIC1612 - ADAPTIVE CONTROL SYSTEMS

SATHYABAMA
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COURSE OBJECTIVES

- To make the student familiarize with adaptive control schemes and MRAS
- To identify the techniques of linear and nonlinear systems with unknown parameters
- To introduce stability robustness concepts with protection systems.

Model Reference Adaptive Systems

https://www.youtube.com/watch?v=j0nz0csr6Iq
https://www.youtube.com/watch?v=vL-gkX41Lk0
https://www.youtube.com/watch?v=dSbybMAalec

https://www.sciencedirect.com/topics/engineering/adaptive-control-system

Adaptive Control System

UNIT 1 INTRODUCTION TO ADAPTIVE CONTROL SYSTEM **9 Hrs.**

Definition of adaptive control system - functions of adaptive control - Different approaches to Adaptive Control - gain scheduling - Relay feedback

UNIT 2 IDENTIFICATION OF ADAPTIVE CONTROL **9 Hrs.**

Conventional methods of Identifications - step response, impulse response, Bode plot - Identification of linear time-invariant systems - Adaptive observers - Sufficient richness condition for parameter convergence - Equation error and output error methods

UNIT 3 MODEL REFERENCE ADAPTIVE SYSTEMS (MRAS) **9 Hrs.**

The need for MRAS - An over view of adaptive control systems - Mathematical description of MRAS - Design hypothesis - Equivalent representation of MRAS.

UNIT 4 CLASSIFICATION OF ADAPTIVE CONTROL **9 Hrs.**

Definitions - Auto tuning - Types of adaptive control - Recent trends in self-tuning - Robustness studies - Multivariable systems - Model updating - General-purpose adaptive regulator

UNIT 5 ADAPTIVE PROTECTION **9 Hrs.**

Need of Adaptive Protection in the system - Techniques for adaptive strategies in distance protection - Synchro-phasor based adaptive protection schemes - protection schemes - SCADA based protection systems - FTA - Testing of Relays.

Max. 45 Hours

Adaptive Control System

TEXT / REFERENCE BOOKS

1. Astrom K.J, Wittenmark B, Adaptive Control, Addison-Wesley, 2nd edition, 1995
2. Shankar Sastry, Marc Bodson, "Adaptive Control", Prentice Hall of India (P) Ltd., 1993.
3. Chalam V.V "Adaptive Control Systems - Techniques & Applications" - Marcel Dekker Inc
4. Chang C. Hong, Tong H. Lee and Weng K. Ho, Adaptive Control, ISA press, Research Triangle Park, 1993.

END SEMESTER EXAM QUESTION PAPER PATTERN

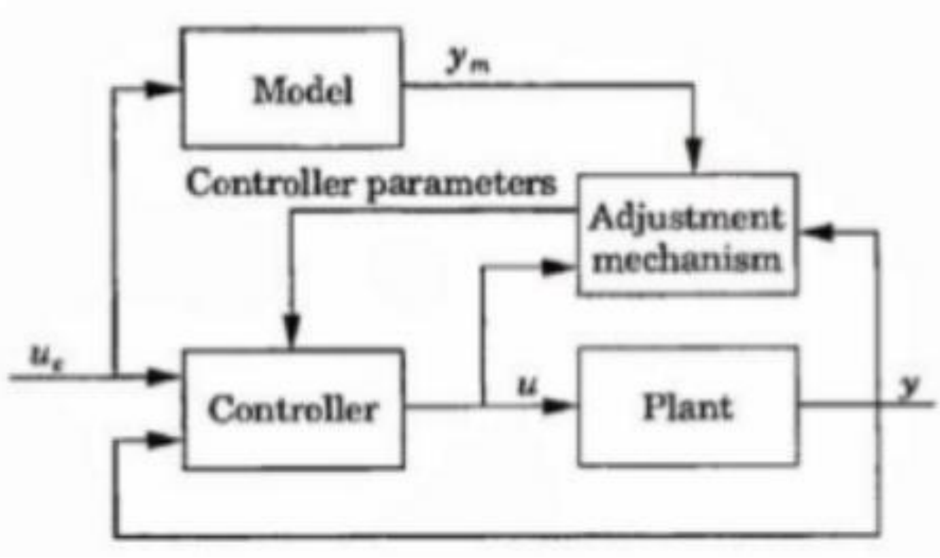
Max. Marks : 100 **Exam Duration : 3 Hrs.**

PART A : 2 Questions from each unit, each carrying 2 marks **20 Marks**

PART B : 2 Questions from each unit with internal choice, each carrying 16 marks **80 Marks**

Model Reference Adaptation Systems (MRAS)

MRAS is an important adaptive controller. It may be regarded as an adaptive servo system in which the desired performance is expressed in terms of a reference model, which gives the desired response to a command signal. This is a convenient way to give specifications for a servo problem. A block diagram of the system is shown in Figure 1.1. The system has an ordinary feedback loop composed of the process and the controller in addition to another feedback loop that changes the controller parameters. The parameters are changed on the basis of feedback from the error, which is the difference between the output of the system and the output of the reference model. The ordinary feedback loop is called the inner loop, and the parameter adjustment loop is called the outer loop. The mechanism for adjusting the parameters in a model-reference adaptive system can be obtained in two ways: by using a gradient method or by applying stability theory.



Adaptive Control System

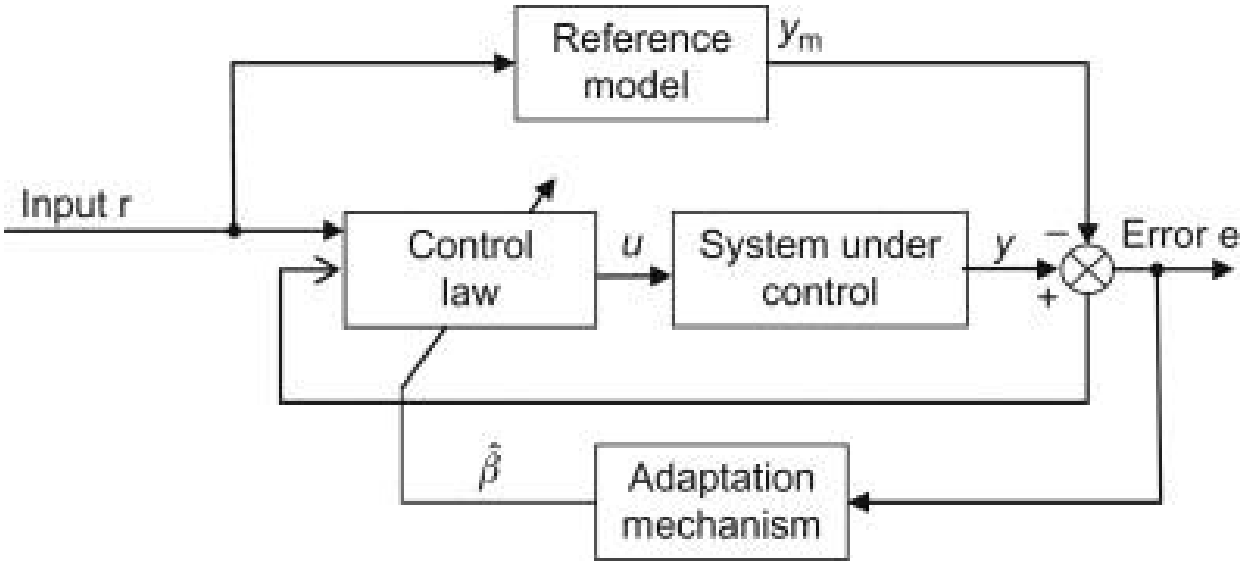
- The Model-Reference Adaptive system (MRAS) was originally proposed to solve a problem in which the performance specifications are given in terms of a reference model.
- This model tells how the process output ideally should respond to the command signal.
- The Adaptive Controller has two loops. The inner loop consists of the process and an ordinary feedback controller.
- The outer loop adjusts the controller parameters in such a way that the error, which is the difference between the process output y and model output ym is small.
- The MRAS was originally introduced for flight control.
- In this case, the reference model describes the desired response of the aircraft to joystick motions.
- Model reference adaptive systems were originally derived for deterministic continuous systems.

To estimate the uncertain plant parameters (or, equivalently, the corresponding controller parameters) on-line based on the measured system signals and use the estimated parameters in the control input computation.

Adaptive Control System

Model Reference Adaptive Control (**MRAC**) is a direct **adaptive** strategy with some adjustable controller parameters and an adjusting mechanism to adjust

The general architecture of a model reference adaptive control system is shown in Figure and contains four basic components (units)



1. The system to be controlled that involves unknown parameters
2. A reference model for the overall and compact determination of the desired system output
3. A feedback controller with adaptive (adjusted) parameters
4. An adaptation mechanism for updating the controller parameters

Adaptive Control System

It is assumed that the structure of the controlled system is known, and only its parameters are unknown. The reference model provides the ideal response of the system that must be achieved through the parameters adaptation. The control law is parameterized with a number of adaptable parameters. The control law must have the ability to follow perfectly or asymptotically the reference response (trajectory). This means that when the system parameters are exactly known, the respective controller parameters must make the system output identical with the output of the reference model. The adaptation law searches to find the parameter values which assure that the system response under MRAC is ultimately the same with the reference model response, that is, assure convergence of the error between the two responses to zero. Essentially, the basic difference between conventional and adaptive controllers is the use of such parameter adaptation law. The two most popular methods of designing the controller's adaptation law are as follows:

1. The steepest descent method
2. The Lyapunov stability method

Adaptive Control System

7.2.1.1 Steepest Descent Parameter Adaptation Law

This scheme is known as MIT rule since it was developed at the Massachusetts Institute of Technology. Let β be the parameter vector, and e the error between the actual and reference outputs. We use the following criterion:

$$I(\beta) = \frac{1}{2}\mathrm{e}^2$$

To reduce $I(\beta)$, it is logical to vary the parameters in the opposite direction shown by $\mathrm{d}I/d\beta$, that is:

$$\frac{\mathrm{d}\beta}{\mathrm{d}t} = -\gamma\frac{\mathrm{d}I}{\mathrm{d}\beta} = -\gamma e\frac{\vartheta e}{\vartheta\beta} \tag{7.1}$$

For slowly varying parameters (much slower than the other variables of the system), the derivative $\vartheta e/\vartheta\beta$ can be computed for β constant. This derivative is called *sensitivity derivative*. If we use the error criterion:

$$I(\beta) = |e|,$$

then the adaptation law is:

$$\frac{\mathrm{d}\beta}{\mathrm{d}t} = -\gamma\frac{\vartheta e}{\vartheta\beta}\mathrm{sgn}(e) \tag{7.2}$$

where $\mathrm{sgn}(e)$ is the known *signum function*. The adaptation laws are applicable to both linear and nonlinear system. In all cases, the error dynamics must first be determined.

7.2.1.2 Lyapunov-Based Adaptation Law

This adaptation law assumes right from the beginning that the error $e(t)$ will really converge to zero. For clarity, we will illustrate this method for the simple scalar system:

$$\dot{y}(t) = -ay(t) + bu(t) \tag{7.3}$$

where $u(t)$ is the control variable and $y(t)$ is the measured output. The stable reference model is assumed to be:

$$\dot{y}_{\mathrm{m}}(t) = -a_{\mathrm{m}} y_{\mathrm{m}}(t) + b_{\mathrm{m}} v(t), \quad a_{\mathrm{m}} > 0 \tag{7.4}$$

The control law is selected as:

$$u(t) = -k_1 y(t) + k_0 v(t) \tag{7.5}$$

Defining the output error $e = y - y_{\mathrm{m}}$, we get the dynamic equation for the closed-loop error, obtained using the control law (7.5), as:

$$\dot{e}(t) = -a_{\mathrm{m}} e + (a_{\mathrm{m}} - a - bk_1) y + (bk_0 - b_{\mathrm{m}}) v \tag{7.6}$$

Clearly, if $a + bk_1 = a_{\mathrm{m}}$, that is, $k_1 = (a_{\mathrm{m}} - a)/b$, and $bk_0 - b_{\mathrm{m}} = 0$ (i.e., $k_0 = b_{\mathrm{m}}/b$), the closed loop system is identical with the reference model and so $e(t) \to 0$ for $t \to \infty$. To construct an adaptation law that leads the controller parameters k_0 and k_1 to the above ideal values $k_0 = b_{\mathrm{m}}/b$ and $k_1 = (a_{\mathrm{m}} - a)/b$, we use the following candidate Lyapunov function:

$$V(e, k_0, k_1) = \frac{1}{2}\left[e^2 + \frac{1}{b\gamma}(bk_1 + a - a_{\mathrm{m}})^2 + \frac{1}{b\gamma}(bk_0 - b_{\mathrm{m}})^2\right] \tag{7.7}$$

This function satisfies the first three properties of Lyapunov functions, and has zero value when k_0 and k_1 have the ideal values. Differentiating V, we get:

$$\begin{aligned} \dot{V} &= e\dot{e} + \frac{1}{\gamma}(bk_1 + a - a_{\mathrm{m}})\dot{k}_1 + \frac{1}{\gamma}(bk_0 + b_{\mathrm{m}})\dot{k}_0 \\ &= -a_{\mathrm{m}} e^2 + \frac{1}{\gamma}(bk_1 + a - a_{\mathrm{m}})(\dot{k}_1 - \gamma y e) \\ &\quad + \frac{1}{\gamma}(bk_0 + b_{\mathrm{m}})(\dot{k}_0 + \gamma v e) \end{aligned} \tag{7.8}$$

Thus, we choose the parameter adaptation (updating) laws as:

$$\begin{aligned} \dot{k}_0 &= -\gamma v e \\ \dot{k}_1 &= \gamma y e \end{aligned} \tag{7.9}$$

Then, Eq. (7.6) gives:

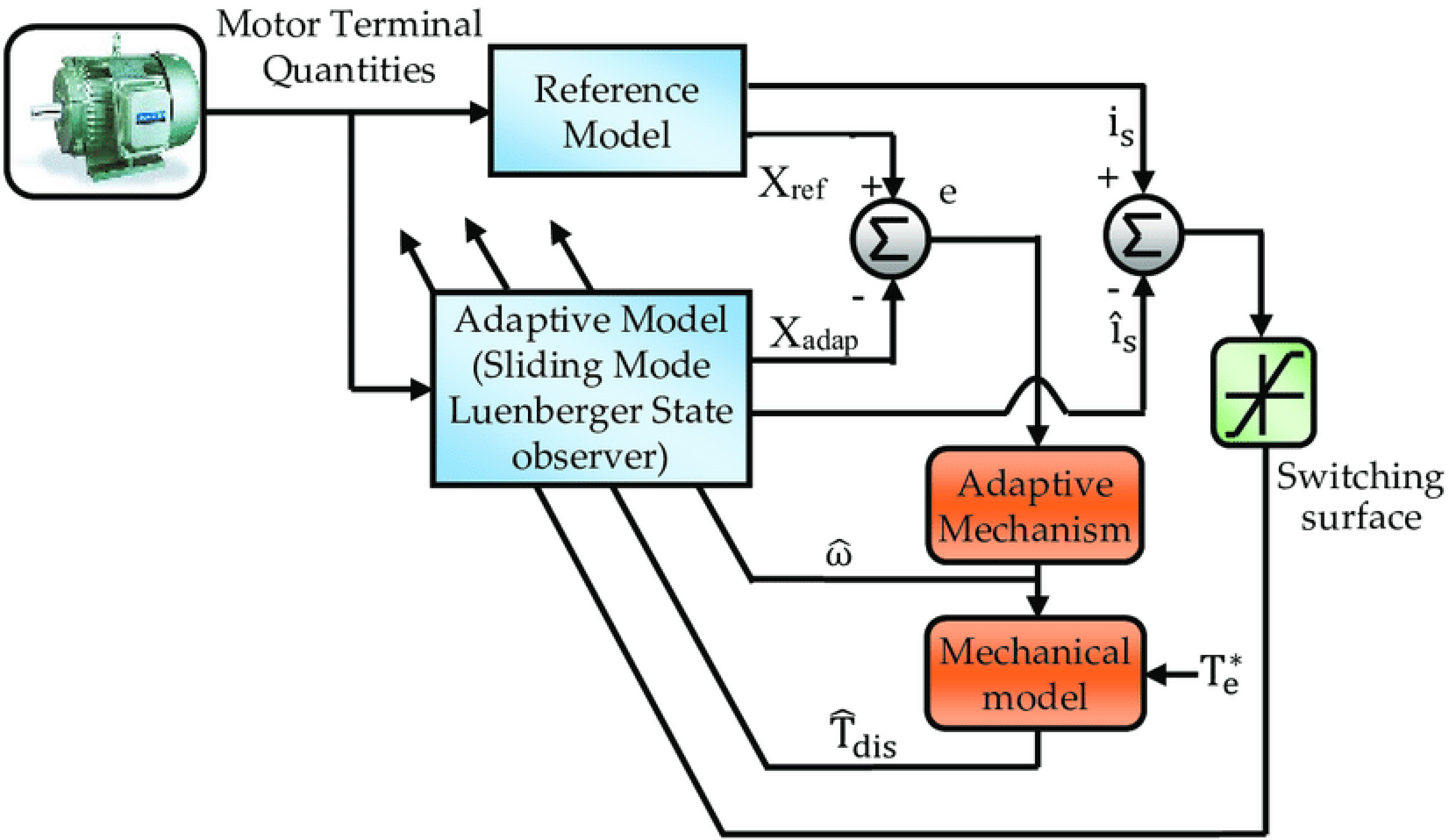
$$\dot{V} = -a_{\mathrm{m}} e^2 < 0 \quad (a_{\mathrm{m}} > 0) \tag{7.10}$$

Therefore, by the Lyapunov stability criterion, $e(t)$ tends asymptotically to zero as $t \to \infty$. Of course, the convergence of k_0 and k_1 to the ideal values is not assured unless some other appropriate conditions are posed. We observe that the adaptation laws (7.9) are of the general form:

$$\dot{\boldsymbol{\beta}} = \gamma \boldsymbol{\psi} \mathbf{e} \tag{7.11}$$

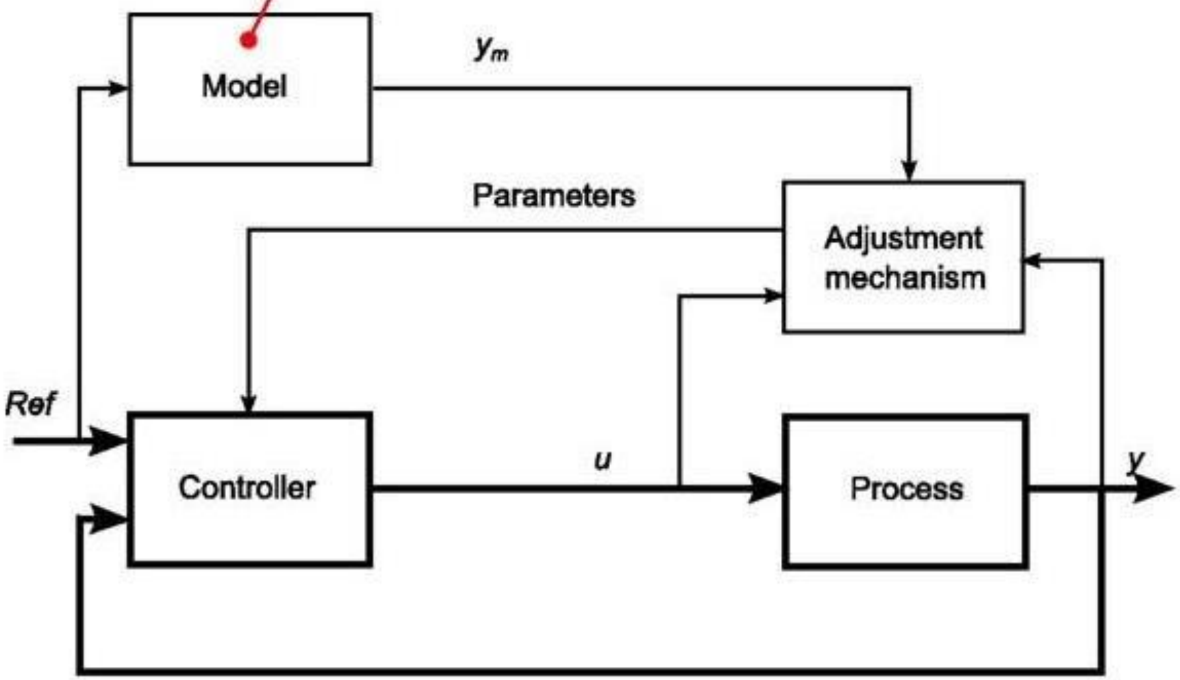
where $\boldsymbol{\beta}$ is the parameter vector, $\mathbf{e}$ is the error between the closed loop output and the reference output, and $\boldsymbol{\psi}$ is a known function depending on v and y. The above Lyapunov adaptation method is applicable to MIMO and nonlinear systems, as it will be shown in the case of WMRs.

Adaptive Control System



Model reference adaptive system, MRAS

If the process output *y* behaves differently from what this model prescribes, the controller is re-tuned to more favourable settings. Conceptually, MRAS makes any system behave as desired, but this is not possible in practice; for instance, you cannot make a ferry behave like a sailing boat.



Model Reference Adaptation Systems (MRAS)

Over view of model reference adaptive system?

Model reference adaptation systems (MRAS) Adaptive Control .Model Reference Adaptation Systems (MRAS) MRAS is an important adaptive controller. It may be regarded as an adaptive servo system in which the desired performance is expressed in terms of a reference model, which gives the desired response to a command signal. This is a convenient way to give specifications for a servo problem

MRAS is an important adaptive controller. It may be regarded as an adaptive servo system in which the desired performance is expressed in terms of a reference model, which gives the desired response to a command signal.

The reference model is based on a set of equations which does not include the parameter to be estimated. On the contrary, the adaptive model is used to observe the same state variables with different sets of equations employing different inputs which include the parameter to be estimated. The stability of a drive system is achieved by minimizing the error between the signals based on either rotor flux or back EMF or reactive power or active power or electromagnetic torque or obtained from the two models. A set of adaptive laws such as Popov's criterion of hyper stability , Lyapunov stability theorem and recursive least-square (RLS) algorithm has been widely considered to minimizes the error signal. One such adaptation mechanism based on the hyper stability concept with the two blocks in the feedback systems. A system is said to be asymptotically hyper stable if the linear time-invariant forward-path transfer matrix is strictly real-positive and that the non-linear feedback (which includes the adaptation mechanism satisfies Popov's criterion for hyper stability . The adaptive law based on Lyapunov stability theory is designed for low-order systems and that based on RLS algorithm is suitable for both low- and high-order systems. The RLS-based adaptive law provides a quick convergence rate for the controller adaptation. However, MRAS with RLS-based adaptation law performs better in trajectory tracking and model following.

Introduction

The preliminary idea of MRAS technique in the year 1979 is to adjust the state variables of a system under study using two different sub-models namely, reference model and adaptive model and find out an adaptation mechanism to minimize the error between the two models in order to estimate a desired physical quantity. A basic structure of MRAS .The reference model is based on a set of equations which does not include the parameter to be estimated. On the contrary, the adaptive model is used to observe the same state variables with different sets of equations employing different inputs which include the parameter to be estimated. The stability of a drive system is achieved by minimizing the error between the signals based on either rotor flux or back

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Over view of model reference adaptive system

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Need for model reference adaptive system?

The main purpose of adaptive control is to control of systems which have parameters that are not accurately known. This inaccuracy can arise from changes in environment, such as temperature in thermal systems, density of air or water as in flying vehicles or submarines. Some system changes can be unpredictable, and ordinary closed-loop systems may not respond properly when the system transfer function varies. In many such circumstances, adaptive control is justified. Among many approaches for adaptive control of such systems, the Model Reference Adaptive Control has become a popular and widely accepted approach for incorporating the adaptive feature into an ordinary feedback control system. It was developed during 1960s..

Adaptive control is not suitable for every machining situation. In general, the following characteristics can be used to identify situations where adaptive control can be beneficially applied.

• The in-process time consumes a significant portion of the machining cycle time. There are significant sources of variability in the job for which AC can compensate.

• The cost of operating the machine tool is high.

• The typical jobs involve steels, titanium and high strength alloys.

Function and structure of MRAS with block diagram?

The system has an ordinary feedback loop composed of the process and the controller in addition to another feedback loop that changes the controller parameters. The parameters are changed on the basis of feedback from the error, which is the difference between the output of the system and the output of the reference model. The ordinary feedback loop is called the inner loop, and the parameter adjustment loop is called the outer loop. The mechanism for adjusting the parameters in a model-reference adaptive system can be obtained in two ways: by using a gradient method or by applying stability theory.

Model Reference Adaptive Control strategy is used to design the adaptive controller that works on the principle of adjusting the controller parameters so that the output of the actual plant tracks the output of a reference model having the same reference input.

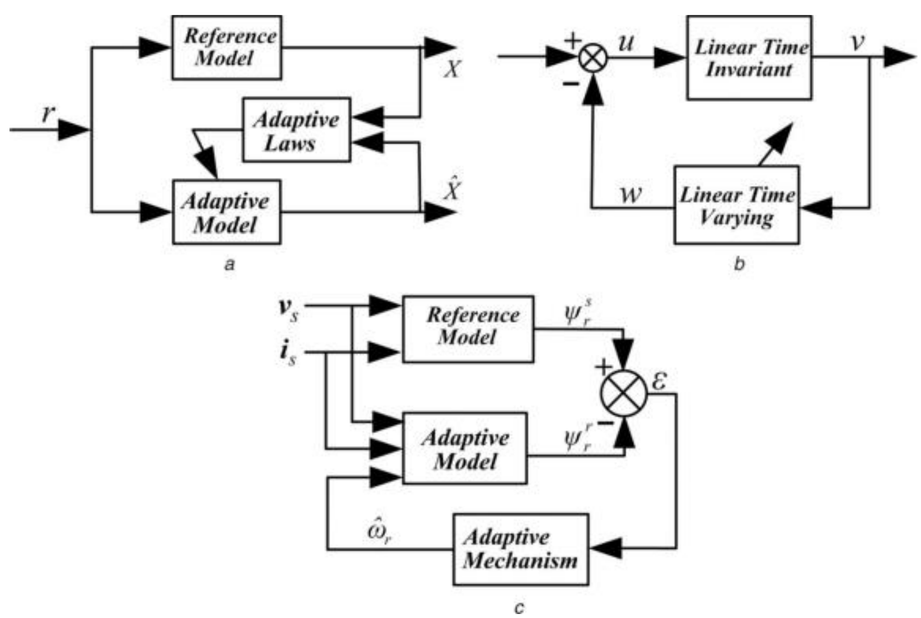


fig a. MRAS

b. Feedback system of MRAS-based control or estimation

c. Rotor-flux-error-based MRAS

4) Mathematical representation of MRAS?

There are many different methods for designing such a controller. When designing an MRAC using the MIT rule, the designer chooses: the reference model, the controller structure and the tuning gains for the adjustment mechanism

. MRAC begins by defining the tracking error, e. This is simply the difference between the plant output and the reference model output:

$$e = y_{sistem} - y_{model}$$

: From this error a cost function of theta (J(theta)) can be formed. J is given as a function of theta, with theta being the parameter that will be adapted inside the controller. The choice of this cost function will later determine how the parameters are updated. Below, a typical cost function is displayed.

$$J(\theta) = \frac{1}{2}e^2(\theta)$$

$$\frac{d\theta}{dt} = -\gamma \frac{\delta J}{\delta \theta} = -\gamma e \frac{\delta e}{\delta \theta}$$

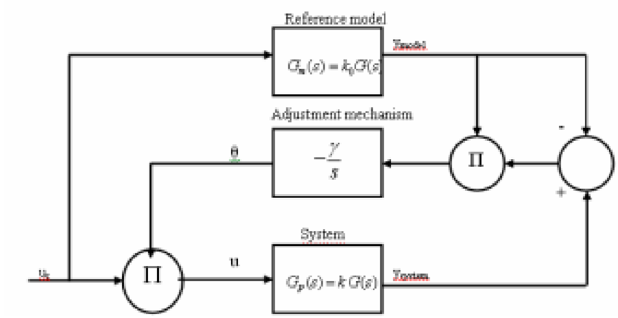
) This relationship between the change in theta and the cost function is known as the MIT rule. The MIT rule is central to adaptive nature of the controller. Note the term pointed out in the equation above labeled "sensitivity derivative". This term is the partial derivative of the error with respect to theta. This determines how the parameter theta will be updated. A controller may contain several different parameters that require updating. Some may be acting n the input. Others may be acting on the output. The sensitivity derivative would need to be calculated for each of these parameters

$$J(\theta) = |e(\theta)|$$

$$\frac{d\theta}{dt} = -\gamma \frac{\delta e}{\delta \theta_c} sign(e)$$

$$\text{where, } sign(e) = \begin{cases} 1, & e > 0 \\ 0, & e = 0 \\ -1, & e < 0 \end{cases}$$

To see how the MIT rule can be used to form an adaptive controller, consider a system with an adaptive feed forward gain. The block diagram is given below



The system model for the adaptive control according to the MIT rule

$$\frac{Y(s)}{U(s)} = kG(s)$$

The constant k for this plant is unknown. However, a reference model can be formed with a desired value of k, and through adaptation of a feed forward gain, the response of the plant can be made to match this model. The reference model is therefore chosen as the plant multiplied by a desired constant k0

$$\frac{Y(s)}{U_C(s)} = k_0G(s)$$

The same cost function as above is chosen and the derivative is show;

$$J(\theta) = \frac{1}{2}e^2(\theta) \longrightarrow \frac{d\theta}{dt} = -\gamma e\frac{\delta e}{\delta\theta}$$

The error is then restated in terms of the transfer functions multiplied by their inputs.

$$e = y - y_m = kGU - G_mU_c = kG\theta U_c - k_0GU_c$$

As can be seen, this expression for the error contains the parameter theta which is to be updated. To determine the update rule, the sensitivity derivative is calculated and restated in terms of the model output:

$$\frac{\delta e}{\delta\theta} = kGU_c = \frac{k}{k_o}y_m$$

Finally, the MIT rule is applied to give an expression for updating theta. The constants k and ko are combined into gamma.

$$\frac{d\theta}{dt} = -\gamma' \frac{k}{k_o} y_m e = -\gamma y_m e$$

The block diagram for this system is the same as the diagram given at the beginning of this example. To tune this system, the values of ko and gamma can be varied.

Mathematical representation of MRAS

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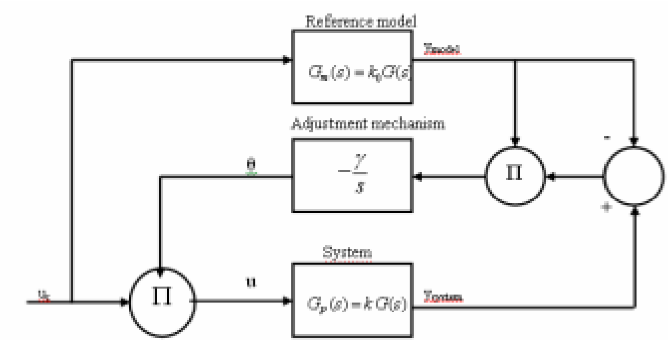

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The block diagram for this system is the same as the diagram given at the beginning of this example. To tune this system, the values of ko and gamma can be varied.

MIT Rule

The MIT rule is the original approach to model-reference adaptive control. The name is derived from the fact that it was developed at the Instrumentation Laboratory (now the Draper Laboratory) at MIT.

To present the MIT rule, we will consider a closed-loop system in which the controller has one adjustable parameter θ. The desired closed-loop response is specified by a model whose output is y_m. Let e be the error between the output y of the closed-loop system and the output y_m of the model. One possibility is to adjust parameters in such a way that the loss function $J(\theta) = \frac{1}{2}e^2$ is minimized.

Procedure

$$\begin{aligned}
\text{Process}: G(s) &= \frac{y}{u} && (1.1)\\
\text{Model}: G_m(s) &= \frac{y_m}{u_c} && (1.2)\\
\text{Control law}: u(t) &= f(u_c, y) && (1.3)\\
\text{Get closed loop from } \boxed{1.1} \ \& \ \boxed{1.3} &: \frac{y}{u_c} && (1.4)\\
\text{Error}: e &= y - y_m && (1.5)\\
\frac{\partial e}{\partial \theta} &= \frac{\partial y}{\partial \theta} && (1.6)\\
\text{MIT Rule}: \frac{d\theta}{dt} &= -\gamma e \frac{\partial e}{\partial \theta} && (1.7)
\end{aligned}$$

Determination of Adaptation Gain

- Consider the plant transfer function $G(s)$.
- Multiply the denominator of $G(s)$ by s and add the term μ to get the characteristic equation

$$sG(s) + \mu = 0$$

where, $\mu = \gamma y_m u_c k$.

- Find μ that places all the roots in left half of $S - plane$.
- If $y_m u_c k = constant \quad \Rightarrow \quad \gamma = \dfrac{\mu}{y_m u_c k}$

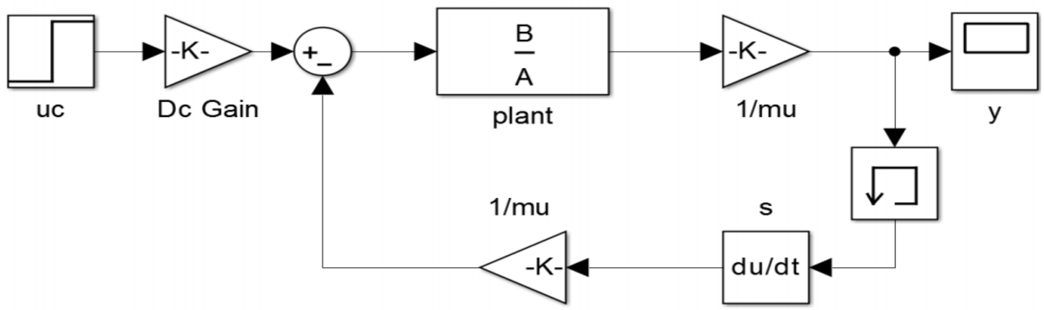

Figure c: Second order system adjustment with first order controller block diagram

Normalized MIT Rule

Procedure

$$\begin{aligned}
\text{Process}: G(s) &= \frac{y}{u} && (1.8)\\
\text{Model}: G_m(s) &= \frac{y_m}{u_c} && (1.9)\\
\text{Control law}: u(t) &= f(u_c, y) && (1.10)\\
\text{Get closed loop from } \boxed{1.8} \,\&\, \boxed{1.10} &: \frac{y}{u_c} && (1.11)\\
\text{Error}: e &= y - y_m && (1.12)\\
\frac{\partial e}{\partial \theta} &= \frac{\partial y}{\partial \theta} = -\varphi && (1.13)\\
\text{Normalized MIT Rule}: \frac{d\theta}{dt} &= \gamma \frac{\varphi e}{\alpha + \varphi^T \varphi} && (1.14)\\
\alpha &> 0 && (1.15)
\end{aligned}$$

We will now show how Lyapunovs stability theory can be used to construct algorithms for adjusting parameters in adaptive systems. To do this, we first derive a differential equation for the error, $e = y - y_m$. This differential equation contains the adjustable parameters. We then attempt to find a Lyapunov function and an adaptation mechanism such that the error will go to zero.When using the Lyaponov theory for adaptive systems, we find that dV/dt is usually only negative semi-definite. The procedure is to determine the error equation and a Lyapunov function with a bounded second derivative.

General Case

Given a continuous time system and the target dynamics

$$\dot{x} = Ax + Bu, \quad \dot{x_m} = A_m x_m + B_m u_c$$

Consider the controller and the error signals

$$u(t) = Mu_c(t) - Lx(t), \quad e(t) = x(t) - x_m(t)$$

If the model-matching problem is solvable, then the error dynamics is

$$\begin{aligned} \frac{de}{dt} &= Ax + Bu - A_m x_m - B_m u_c \\ &= A_m e + (A - A_m - BL)\, x + (BM - B_m)\, u_c \\ &= A_m e + \Psi(x, u_c) \bullet \left(\theta - \theta^0\right) \end{aligned}$$

Consider the following Lyapunov function candidate

$$V = \frac{1}{2}\left[e^T P e + \frac{1}{\gamma}\left(\theta - \theta^0\right)^T \left(\theta - \theta^0\right)\right]$$

The time-derivative of V is

$$\dot{V} = \frac{1}{2} e^T \left[P A_m + A_m^T P\right] e + \left(\theta - \theta^0\right)^T \Psi^T P e + \frac{1}{\gamma}\left(\theta - \theta^0\right)^T \dot{\theta}$$

If we solve the Lyapunov equation for $P = P^T > 0$

$$P A_m + A_m^T P = -Q, \quad Q > 0$$

and choose the update law as

$$\dot{\theta} = -\gamma \Psi^T P e = -\gamma \Psi^T(x, u_c) \bullet P \bullet (x - x_m)$$

then

$$\dot{V} = -\frac{1}{2} e^T(t) Q e(t)$$

and we conclude that $e(t) \to 0$

Applications of MRAS

Until now it has been assumed that

1) process and reference model are of the same order and structure;
2) there are no nonlinearities;
3) there are no stochastic variations in the states of the process or its inputs. In practice, none of these assumptions will be com pletely true. In this section a few solutions will be given to solve these problems. It has been shown that structural differences between process and reference model are not disastrous as long as the reference-model structure contains the major process dynamics and simple adjustment rules are used. The adjustment laws and are such simple laws. More sophisticated algorithms, which give a better performance in the ideal case, fail when only small differences between the structures of process and reference model are present. Nonlinearities in the process (or in the reference model) can partly be treated in a way similar to the structural differences. Nonlinearities which can be considered as variations in the parameters of a simplified model will be compensated for by adjust of the controller ment of r parameters. This requires a relatively high speed of adaptation. More problems are Saturation t are caused by nonlinearities of the is quite type. This type of nonlinearity common to amplifiers, in valves which are completely open or closed, et cetera. In principle there are two possibilities for dealing with this problem: -switching off the adaptation as long as the element 196 is saturated: -modifying the input signal of process and reference model so that no saturation will occur. The latter method has been successfully applied in an adaptive autopilot for ships. No modifications of the adaptive loop itself are required and the proof of stability also remains unchanged. The non-linear element is in fact removed from the control loop. Its important to reduce noisy signals.

The main purpose of adaptive control is to control of systems which have parameters that are not accurately known. This inaccuracy can arise from changes in environment, such as temperature in thermal systems, density of air or water as in flying vehicles or submarines. Some system changes can be unpredictable, and ordinary closed-loop systems may not respond properly when the system transfer function Corresponding author. This paper presents improved new adaptive laws in the design of Model Reference Adaptive Control (MRAS)systems, based on Lyapunov stability theory. It focuses on the standard adaptive laws which were developed based on a Positive Definite Quadratic Lyapunov functions; these standard laws make the derivative of the Lyapunov function only negative semi-definite; this feature was observed for the past three decades (1970s, 80s and 90s). However, it is noted that the transient response of the system error converging to zero has been significantly. that employs the integral of square of error signal. The new adaptive laws offer improved transient response of the system error converging to zero–in particular, in a less oscillatory fashion. In addition, these new adaptive laws lead the derivative of the new Lyapunov function to become negative definite, along as the system error is not zero. The paper presents first mathematical development for 1st order and 2nd order systems, having relative degree as unity then, it later presents simulation study, using the MATLAB package.

In MRAC, a reference model is apriority chosen so that it describes the desired response of the plant controller combination. This choice is made by the designer, based on experience.

output is compared with the reference model output; the difference between them, called a system output is used to adjust the controller parameters such a way until this very error signal is driven to zero. In this MRAC, two features play crucial role: Stability of the overall system, including the adaptive mechanism-in the sense that all signals in the entire system remain bounded.

Adaptive Control (MRAC) is one of the main schemes used in adaptive system. Recently MRAC has received considerable attention, and many new approaches have been applied to practical process.

In the MRAC scheme, the controller is designed to realize plant output converges to reference model

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SCHOOL OF MECHANICAL ENGINEERING

DEPARTMENT OF MECHATRONICS ENGINEERING

UNIT – IV - Adaptive Control System – SIC1612

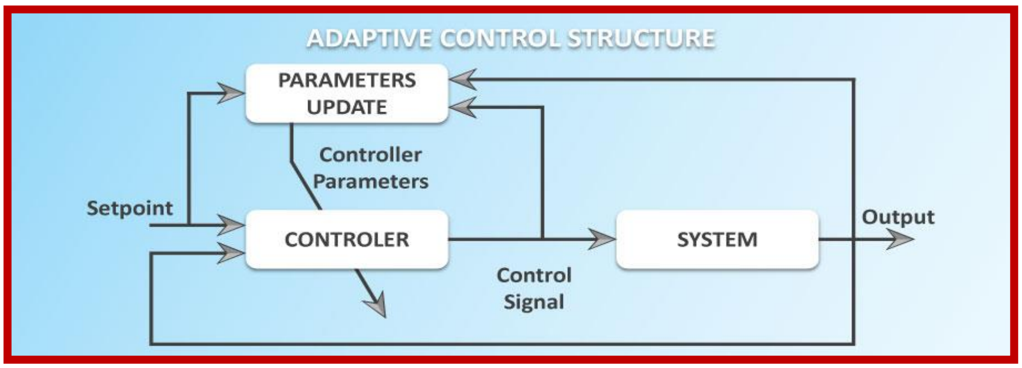
UNIT 4

CLASSIFICATION OF ADAPTIVE CONTROL

Definitions - Auto tuning - Types of adaptive control - Recent trends in self-tuning - Robustness studies - Multivariable systems - Model updating - General-purpose adaptive regulator

Adaptive Control

Adaptive control is a set of techniques that permit to adjust the value of control parameters in real time, permitting to monitor controlled variables even if plant parameters are unknown or if they change over time. This control is a special kind of non-lineal control, and the process can be split in two timelines: rapid time (feedback loop) and slow time (variation of control parameters, which affects to automations).



Types of adaptive control

In general, one should distinguish between:

1. Feedforward adaptive control
2. Feedback adaptive control

as well as between

1. Direct methods
2. Indirect methods
3. Hybrid methods

Direct methods are ones wherein the estimated parameters are those directly used in the adaptive controller. In contrast, indirect methods are those in which the estimated parameters are used to calculate required controller parameters. Hybrid methods rely on both estimation of parameters and direct modification of the control law.

There are several broad categories of feedback adaptive control (classification can vary):

- Dual adaptive controllers – based on dual control theory
  - Optimal dual controllers – difficult to design
  - Suboptimal dual controllers
- Nondual adaptive controllers
  - Adaptive pole placement
  - Extremum-seeking controllers
  - Iterative learning control
  - Gain scheduling
  - Model reference adaptive controllers (MRACs) – incorporate a *reference model* defining desired closed loop performance
    - Gradient optimization MRACs – use local rule for adjusting params when performance differs from reference. Ex.: "MIT rule".
    - Stability optimized MRACs
  - Model identification adaptive controllers (MIACs) – perform system identification while the system is running
    - Cautious adaptive controllers – use current SI to modify control law, allowing for SI uncertainty
    - Certainty equivalent adaptive controllers – take current SI to be the true system, assume no uncertainty
      - Nonparametric adaptive controllers
      - Parametric adaptive controllers
        - Explicit parameter adaptive controllers
        - Implicit parameter adaptive controllers

Applications

When designing adaptive control systems, special consideration is necessary of convergence and robustness issues.

- Self-tuning of subsequently fixed linear controllers during the implementation phase for one operating point;
- Self-tuning of subsequently fixed robust controllers during the implementation phase for whole range of operating points;
- Self-tuning of fixed controllers on request if the process behaviour changes due to ageing, drift, wear, etc.;
- Adaptive control of linear controllers for nonlinear or time-varying processes;
- Adaptive control or self-tuning control of nonlinear controllers for nonlinear processes;
- Adaptive control or self-tuning control of multivariable controllers for multivariable processes (MIMO systems);

Usually these methods adapt the controllers to both the process statics and dynamics. In special cases the adaptation can be limited to the static behavior alone, leading to adaptive control based on characteristic curves for the steady-states or to extremum value control, optimizing the steady state. Hence, there are several ways to apply adaptive control algorithms.

A particularly successful application of adaptive control has been adaptive flight control.[7][8] This body of work has focused on guaranteeing stability of a model reference adaptive control scheme using Lyapunov arguments. Several successful flight-test demonstrations have been conducted, including fault tolerant adaptive control.[9]

Self-tuning

In control theory a **self-tuning** system is capable of optimizing its own internal running parameters in order to maximize or minimize the fulfilment of an objective function; typically the maximization of efficiency or error minimization.

Self-tuning and auto-tuning often refer to the same concept. Many software research groups consider auto-tuning the proper nomenclature.

Self-tuning systems typically exhibit non-linear adaptive control. Self-tuning systems have been a hallmark of the aerospace industry for decades, as this sort of feedback is necessary to generate optimal multi-variable control for non-linear processes. In the telecommunications industry, adaptive communications are often used to dynamically modify operational system parameters to maximize efficiency and robustness.

Self-tuning systems are typically composed of four components: expectations, measurement, analysis, and actions. The expectations describe how the system should behave given exogenous conditions.

Measurements gather data about the conditions and behaviour. Analysis helps determine whether the expectations are being met- and which subsequent actions should be performed. Common actions are gathering more data and performing dynamic reconfiguration of the system.

Self-tuning (self-adapting) systems of automatic control are systems whereby adaptation to randomly changing conditions is performed by means of automatically changing parameters or via automatically determining their optimum configuration.[2] In any non-self-tuning automatic control system there are parameters which have an influence on system stability and control quality and which can be tuned. If these parameters remain constant whilst operating conditions (such as input signals or different characteristics of controlled objects) are substantially varying, control can degrade or even become unstable. Manual tuning is often cumbersome and sometimes impossible. In such cases, not only is using self-tuning systems technically and economically worthwhile, but it could be the only means of robust control. Self-tuning systems can be with or without parameter determination.

In systems with parameter determination the required level of control quality is achieved by automatically searching for an optimum (in some sense) set of parameter values. Control quality is described by a generalised characteristic which is usually a complex and not completely known or stable function of the primary parameters. This characteristic is either measured directly or computed based on the primary parameter values. The parameters are then tentatively varied. An analysis of the control quality characteristic oscillations caused by the varying of the parameters makes it possible to figure out if the parameters have optimum values, i.e.. if those values deliver extreme (minimum or maximum) values of the control quality characteristic. If the characteristic values deviate from an extremum, the parameters need to be varied until optimum values are found. Self-tuning systems with parameter determination can reliably operate in environments characterised by wide variations of exogenous conditions.

In practice systems with parameter determination require considerable time to find an optimum tuning, i.e. time necessary for self-tuning in such systems is bounded from below. Self-tuning systems without parameter determination do not have this disadvantage. In such systems, some characteristic of control quality is used (e.g., the first time derivative of a controlled parameter). Automatic tuning makes sure that this characteristic is kept within given bounds. Different self-tuning systems without parameter determination exist that are based on controlling transitional processes, frequency characteristics, etc. All of those are examples of closed-circuit self-tuning systems, whereby parameters are automatically corrected every time the quality characteristic value falls outside the allowable bounds. In contrast, open-circuit self-tuning systems are systems with para-metrical compensation, whereby input signal itself is controlled and system parameters are changed according to a specified procedure. This type of self-tuning can be close to instantaneous. However, in order to realise such self-tuning one needs to control the environment in which the system operates and a good enough understanding of how the environment influences the controlled system is required.

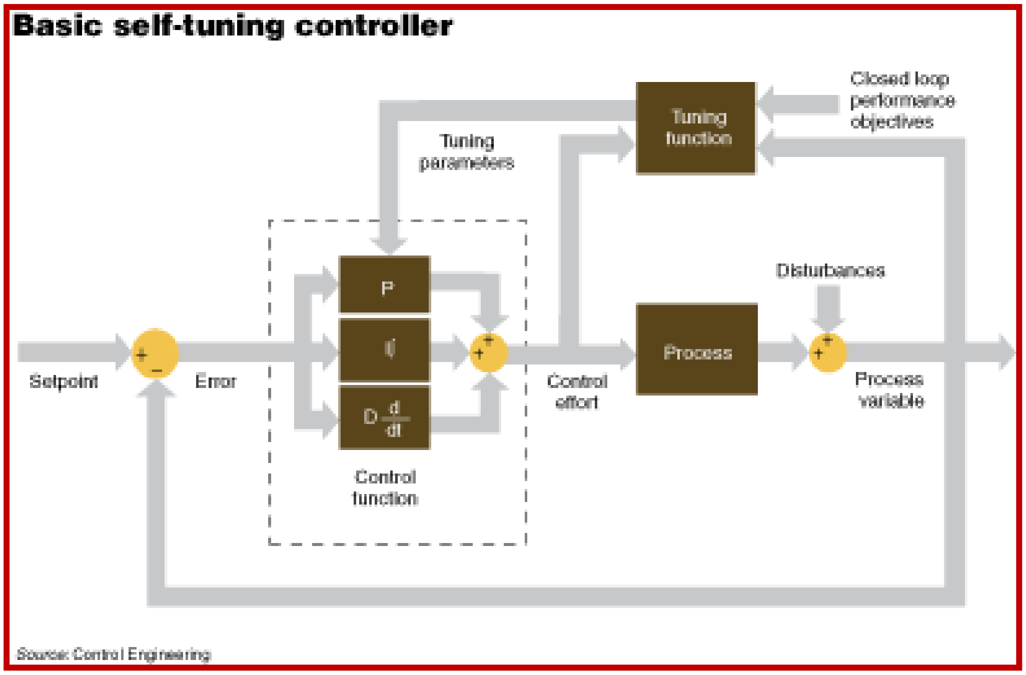
In practice self-tuning is done through the use of specialised hardware or adaptive software algorithms. Giving software the ability to self-tune (adapt):

1. Facilitates controlling critical processes of systems;
2. Approaches optimum operation regimes;
3. Facilitates design unification of control systems;
4. Shortens the lead times of system testing and tuning;
5. Lowers the criticality of technological requirements on control systems by making the systems more robust;
6. Saves personnel time for system tuning.

Fundamentals of Self-Tuning Control

Although proportional-integral-derivative controllers or "PID loops" have been the *de facto* standard of industrial feedback control for more than 65 years, they're not always easy to use. For PID loops to perform up to their potential, they must first be tuned to fit each application, then periodically re-tuned to maintain the desired closed-loop behavior.

"Auto-tuning" controllers can help by automatically generating suitable tuning parameters upon request. With the control function disabled, the operator need only press the "tune" button and watch as the controller's tuning function exercises the process until enough input/output data are available to quantify the process's natural behavior.



A self-tuning controller includes a traditional PID control function as well as a self-tuning function that tries to maintain optimal closed-loop performance by continuously updating the controller's P, I, and D tuning parameters. An auto-tuning controller is similar except that it performs its tuning operation justonce, then initiates closed-loop control using the parameters it has computed. Many commercial PIDcontrollers include both auto-tuning and self-tuning options, and many vendors use those two expressionsinterchangeably.

The tuning function can then recommend a set of P, I, and D tuning parameters that will produce the desired closed-loop behavior once the feedback control function is turned back on. Most auto-tuning techniques simply mimic the steps that an experienced control engineer would execute before bringing a loop on line for the first time. (See "Auto-Tuning Control Using Ziegler-Nichols," *Control Engineering* , October 2006.)

Continuous re-tuning or "self-tuning" is a more difficult challenge because the tuning and the control functions operate simultaneously. The controller must continue to maintain the process variable at a specified level as it tries to learn how the process variable reacts to control efforts. (See the "Basic self-tuning controller" graphic.)

Unfortunately, those are conflicting objectives. Maintaining a constant process variable deprives the tuning function of any useful insight into the behavior of the process, whereas exercising the process to see how it will react to a control effort defeats the purpose of the control function.

Fortunately, there are times during the normal course of closed-loop operation when the control effort and the process variable fluctuate anyway, and most self-tuners are designed to take advantage of those situations.

Setpoint tuning

A setpoint change provides an especially valuable demonstration of a process's input/output behavior. Without taking the loop off-line, the self-tuning function can observe how the process variable reacts to each control effort as the control function attempts to achieve the new setpoint using its current tuning parameters. If that reaction proves to be too sluggish, the tuning function can substitute more aggressive tuning parameters or vice-versa.

One way to do so would be to treat the entire closed-loop system as a single process and the setpoint change as a step test that yields the overall gain and time constant(s) for the closed-loop system. The corresponding values for the open-loop process could then be derived from those results, and new tuning parameters could be computed using any number of traditional tuning rules. Yokogawa's UT100 temperature controller employs a variation on this procedure that is based on the Ziegler-Nichols step response tuning rules. (See "Loop Tuning Fundamentals," *Control Engineering* , July 2003.)

Unfortunately, setpoint changes tend to be rare in many process control applications where the controller's objective is to maintain a given pressure, level, flow rate, or temperature at one specific value forever. Setpoint tuning is more useful in batch applications, such as multi-phase heating and cooling operations where setpoint changes are more frequent.

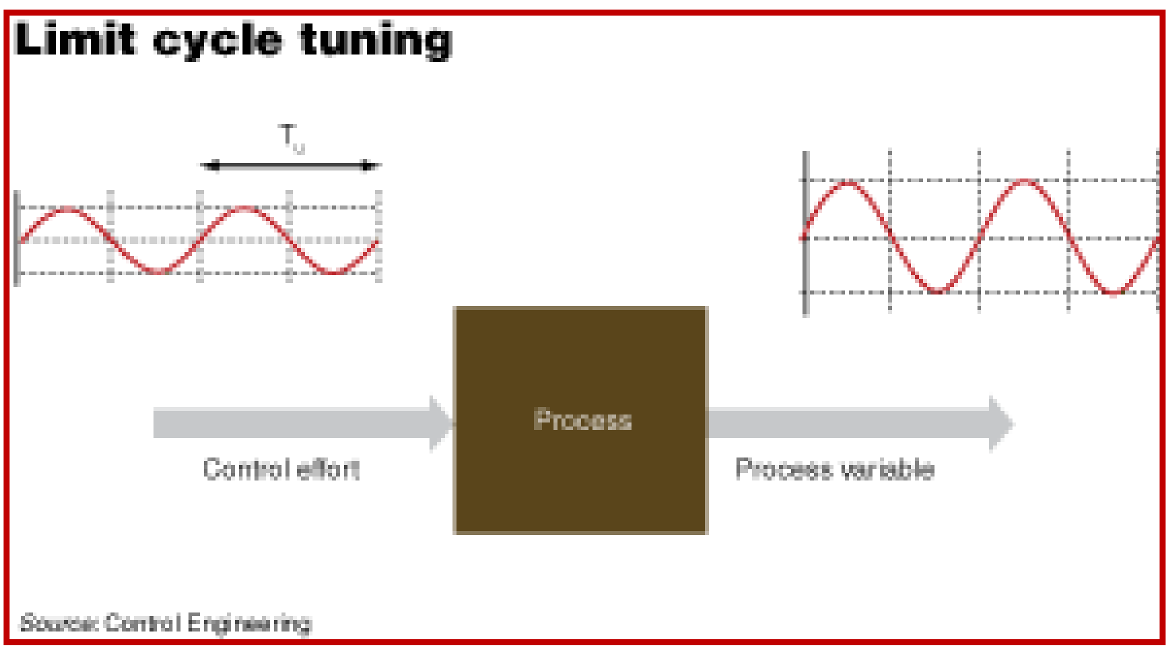
Disturbance tuning

Re-tuning a loop based on a process's reaction to a disturbance is even trickier. The control effort and process variable do fluctuate as the control function attempts to compensate for the disturbance, but it isn't always obvious whether the process variable is reacting to the control effort, additional disturbances, measurement noise, or a combination of all three effects. If the tuning function assumes that all process' variable fluctuations are due to the control effort, then its understanding of the process behavior could end up skewed, and its revised tuning parameters could prove less than optimal.

The easiest fix to this problem is to require operator supervision of the tuning function. Upon observing additional disturbances after the re-tuning has begun, the operator could abort the tuning operation and wait for another solitary disturbance to come along. However, requiring operator intervention defeats one of the main purposes of an otherwise autonomous self-tuning controller.

One way to eliminate the need for an operator's judgment is to enable the tuning function only when the control effort and process variable have begun a "limit cycle" or "hunting." A limit cycle occurs when overly aggressive tuning causes the control function to over-react to an error between the process variable and setpoint. The resulting control effort is so large that it drives the process variable past the setpoint, resulting in a new error just as large as the original but in the opposite direction. The control function then reverses course and repeats the mistake *ad infinitum* , causing a series of sustained oscillations.

Not only is a limit cycle an easily detected indication that re-tuning is required, it gives the tuning function plenty of input / output data to work with when computing an improved set of tuning parameters. The UT100 offers this option as well, using tried-and-true Ziegler-Nichols ultimate sensitivity method (see "Loop Tuning Fundamentals" above). The SA and CB series of digital temperature controllers from RKC Instruments, the E5 series of process controllers from Omron Electronics, and the GFX4/GFXTERMO4 power controllers from Gefran also use limit cycles for on-the-fly loop tuning. (See the "Limit cycle tuning" graphic.)



Some self-tuning controllers wait for a limit cycle to occur before attempting to re-tune the loop. The current tuning parameters and the period of the limit cycle (Tu) are allthat's needed to re-tune the loop by the Ziegler-Nichols ultimate sensitivity method.

Alternative techniques

However, a self-tuning controller that waits for a limit cycle to occur before initiating a remedial re-tuning operation will cause much more variability than some processes can tolerate and allow poor tuning to go uncorrected for extended periods. The self-tuning function might also have trouble distinguishing between actual limit cycles and periodic oscillations due to inter-loop coupling, deadband in a control valve, or cyclical disturbances.

A more sophisticated alternative is to look for clues about the process's behavior in all of the input/output data, not just purely sinusoidal limit cycles. The gammadue Series X5 process controller from Ascon Corp. (also private-labeled as the Platinum Series of process controllers from Athena Controls) does so by analyzing the control effort and process variable in the frequency domain after each disturbance.

InSight, the self-tuning function available for the DeltaV automation system from Emerson Process Management, creates a mathematical model of the input / output data from which appropriate tuning parameters can be derived via IMC (internal model-based control) or Lambda tuning rules. It then indicates how well it understands the behavior of the process based on how well the most recent input / output data fits the current model. A tighter fit means a more accurate model and more reliable tuning parameters.

InSight also uses its process models to generate a "tuning index" that shows the expected percent change in variability that the new tuning parameters will achieve once implemented. The tuning index can also indicate which loops need retuning.

Automatic, but not simple

Not surprisingly, most vendors of self-tuning technology hesitate to reveal exactly how they achieve all these features and functions. And though the basic PID control algorithm is widely known, the mechanisms by which a particular self-tuning controller analyzes the available input/output data and generates tuning parameters are generally too complex to explain anyway.

That can be a problem for the plant engineer who is faced with the possibility of entrusting control of his process to a mysterious black box. It's not possible to ascertain in advance whether the specific self-tuning technology under consideration will actually work for a particular application. Case histories can help establish credibility for a given manufacturer's strategy, but performance cannot be guaranteed.

The uncertainties of self-tuning technology become particularly evident when the self-tuning function generates each new set of tuning parameters. Unless an operator reviews results before they are implemented or the self-tuning function somehow knows whether or not it has generated a reliable answer, there may be times when new tuning parameters make the loop's subsequent performance worse, not better.

Benefits

Ironically, poor performance of the control function often leads to more dramatic fluctuations in the control effort and process variable, which in turn gives the tuning function much more useful information to work with. Still, it is helpful if the tuning function can recognize problems and flag questionable results. A Honeywell Universal Digital Controller equipped with the Accutune III algorithm knows when it has computed P, I, and D parameters that aren't realistic and so informs the operator.

Even though self-tuning technology has yet to be perfected, its benefits can be worth the risks. A process that demonstrates time-varying behavior due to long-term effects, such as equipment wear or fluctuations in ambient conditions, can be difficult to control with a fixed set of tuning parameters. A self-tuning controller can track the process's changing gains and time constants and adapt its tuning to match.

Even a stationary process can demonstrate variable gains and time constants if it is sufficiently non-linear. Controlling pH, for example, requires more conservative control efforts near the equivalence point. A self-tuning controller that can detect the increased gain of the process as the batch is close to being neutralized can throttle back its own tuning accordingly.

Robust Parameter Design and Process Robustness Studies

- **Robust parameter design (RPD):** an approach to product realization activities that emphasizes choosing the levels of controllable factors (parameters) in a process or product to achieve two objectives:
  - To ensure that the *mean* of the output response is at a desired level or target
  - To ensure that the variability around this target value is as small as possible
- When an RPD study is conducted on a process, it is usually called a **process robustness study**
  - Four operators for layout 1
  - Four operators for layout 2
- **Developed by Genichi Taguchi (1980s)**

•**Before Taguchi, (RPD was often done by *overdesign* – expensive**

• Controversy about experimental procedures and data analysis methods (Taguchi's methods are usually inefficient or ineffective)

• **Response surface methodology (RSM) was developed as an approach to the RPD problem**

•**Certain types of variables cause variability in the important system response variables (*noise variables*** or ***uncontrollable variables***)

•A robust design problem usually focuses on one or more of the following

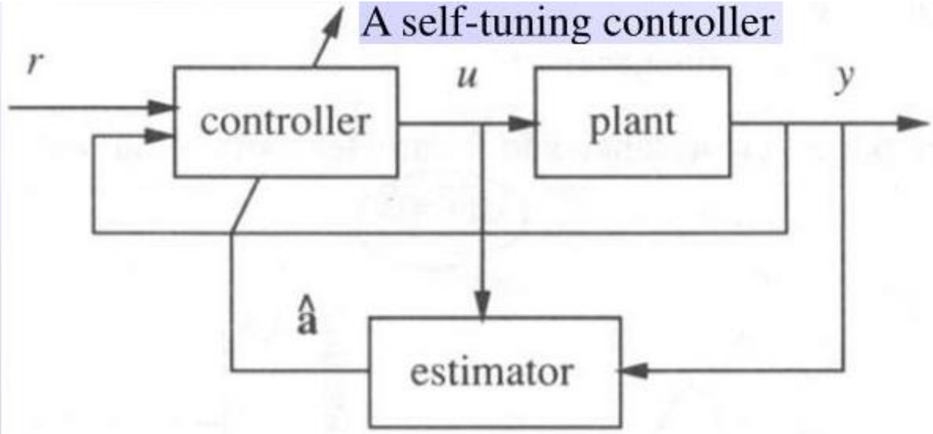
- Designing systems that are insensitive to environmental factors that can affect performance once the system is deployed in the field
- Designing products so that they are insensitive to variability transmitted by the components of the system
- Designing processes so that the manufactured product will be as close as possible to the desired target specifications, even though some process variables are impossible to control precisely
- Determining the operating conditions for a process so that the critical process characteristics are as close as possible to the desired target values and the variability around this target is minimized

•Self-tuning Controller

-If the plant parameters are not known, it is intuitively reasonable to replace them by their estimated values, as provided by a parameter estimator.

-A controller obtained by coupling a controller with an online (recursive) parameter estimator is called a self-tuning controller.

A self-tuning controller



â --- estimated parameters

•Certainty Equivalence

-The controller parameters are computed from the estimates of the plant parameters as if they were the true plant parameters.

•Indirect & Direct Adaptive Control

-Indirect adaptive control:

Estimates the plant parameters then computes the controller parameters.

-Direct adaptive control:

Re-parameterize the plant model using controller parameters (which are also unknown, of course), and then use standard estimation techniques on such a model.

Example 8.2：Self-tuning control of the unknown mass

The simplest estimation

$$\hat{m}(t) = \frac{u(t)}{\ddot{x}}$$

However, considerable noise may be in the measurement ,and the acceleration $\ddot{x}$ may be close to zero.

A better approach is to estimate the parameter using a least-squares approach, *i.e.*, choosing the estimate in such a way that the total prediction error

$$J = \int_0^t e^2(r)dr$$ is minimal,

the prediction error *e* is defined as

$$e(t) = \hat{m}(t)\ddot{x}(t) - u(t)$$

The total error minimization can potentially average out the effects of measurement noise.

$$\hat{m} = \frac{\int_0^t wudr}{\int_0^t w^2 dr} \qquad (8.11)$$

$$w = \ddot{x}$$

P(t): estimation gain, its update is obtained by

$$\frac{d}{dt}[P^{-1}] = w^2$$

Then, the differentiation of Equation (8.11) can be written as

$$\frac{d}{dt}[P^{-1}\hat{m}] = w^2\dot{\hat{m}} = wu$$

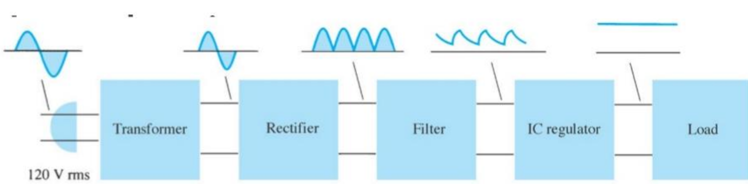
$$\Rightarrow P^{-1}\dot{\hat{m}} = w(-w\hat{m} + u) = -we$$

$$\therefore \dot{\hat{m}} = -Pwe$$

$$P^{-1}\hat{m} = \int_0^t wudr$$

leads to

$$P^{-1}\hat{m} = \int_0^t wudr$$



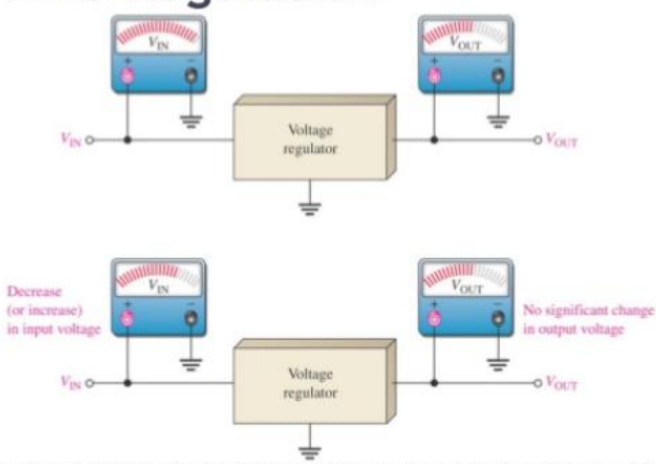
- ***Filter***: a circuit used to reduce the fluctuation in the rectified output voltage or ripple. This provides a ***steadier*** dc voltage.
- ***Regulator***: a circuit used to produces a ***constant*** dc output voltage by reducing the ripple to negligible amount. One part of power supply.

Voltage Regulation

- Two basic categories of voltage regulation are:
  - ❑line regulation
  - ❑load regulation

- The purpose of **line regulation** is to maintain a nearly constant output voltage when the **input voltage** varies.
- The purpose of **load regulation** is to maintain a nearly constant output voltage when the **load** varies

Line Regulation



Line regulation: A change in input (line) voltage does not significantly affect the output voltage of a regulator (within certain limits)

- Line regulation can be defined as the percentage change in the output voltage for a given change in the input voltage.

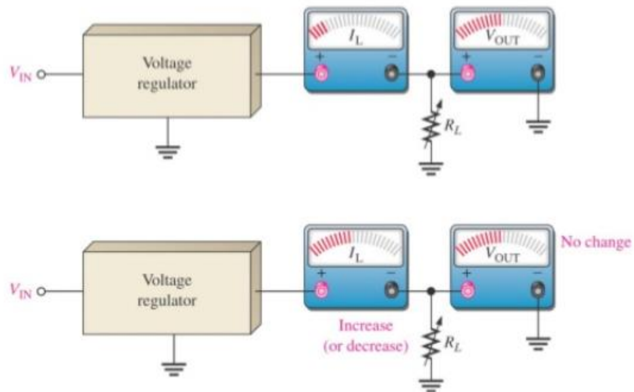
$$Line\ regulation = \left(\frac{\Delta V_{OUT}}{\Delta V_{IN}} \right) \times 100\%$$

Δ means "a change in"

- Line regulation can be calculated using the following formula:

$$Line\,regulation = \frac{(\Delta V_{OUT} / V_{OUT}) \times 100\%}{\Delta V_{IN}}$$

Load Regulation



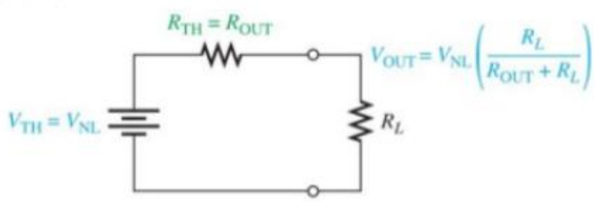
Load regulation: A change in load current (due to a varying R_L) has practically no effect on the output voltage of a regulator (within certain limits)

- Load regulation can be defined as the percentage change in the output voltage from no-load (NL) to full-load (FL).

$$Load\ regulation = \left(\frac{V_{NL} - V_{FL}}{V_{FL}}\right) \times 100\%$$

- Where:
  V_{NL} = the no-load output voltage
  V_{FL} = the full-load output voltage

- Sometimes power supply manufacturers specify the equivalent output resistance (R_{out}) instead of its load regulation.



- R_{FL} equal the smallest-rated load resistance, then V_{FL}:

$$V_{FL} = V_{NL}\left(\frac{R_{FL}}{R_{OUT} - R_{FL}}\right)$$

- Rearrange the equation:

$$V_{NL} = V_{FL}\left(\frac{R_{OUT} - R_{FL}}{R_{FL}}\right)$$

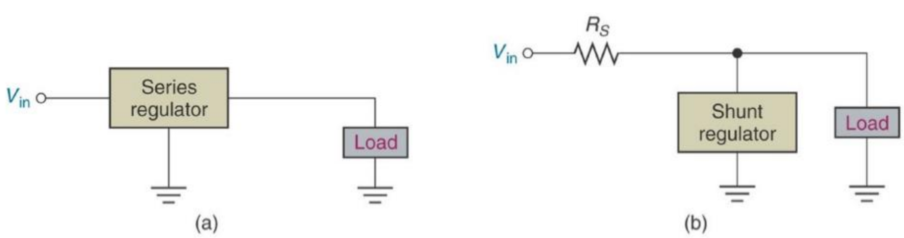
$$Load\ regulation = \frac{V_{FL}\left(\frac{R_{OUT} - R_{FL}}{R_{FL}}\right) - V_{FL}}{V_{FL}} \times 100\%$$

$$Load\ regulation = \left(\frac{R_{OUT} - R_{FL}}{R_{FL}} - 1\right) \times 100\%$$

$$Load\ regulation = \left(\frac{R_{OUT}}{R_{FL}}\right) \times 100\%$$

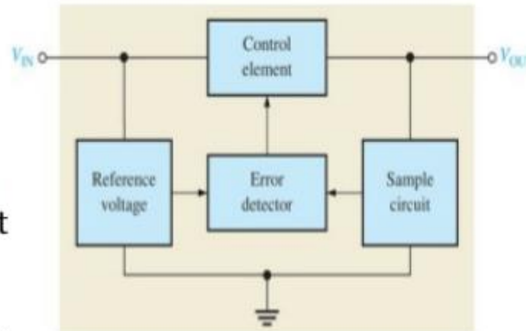
Types of Regulator

- Fundamental classes of voltage regulators are **linear regulators** and **switching regulators**.
- Two basic types of linear regulator are the **series regulator** and the **shunt regulator** .
- The series regulator is connected in **series** with the load and the shunt regulator is connected in **parallel** with the load.

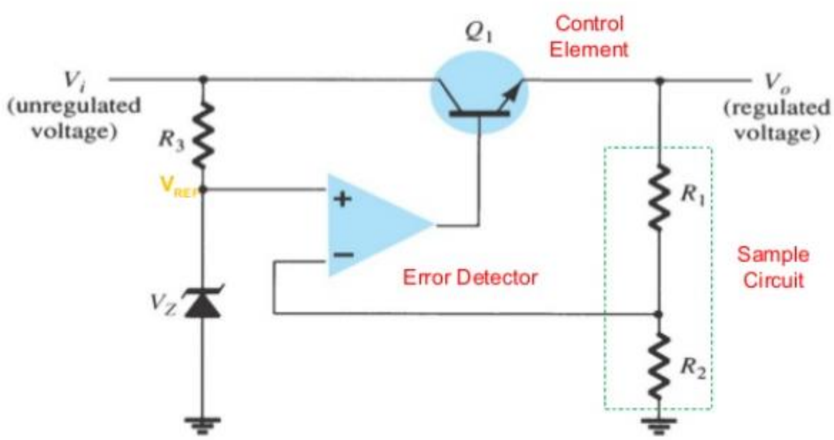


Series Regulator Circuit

- **Control element** in series with load between input and output.
- Output **sample circuit** senses a change in output voltage.
- **Error detector** compares sample voltage with reference voltage → causes control element to compensate in order to maintain a constant output voltage.



Op-Amp Series Regulator

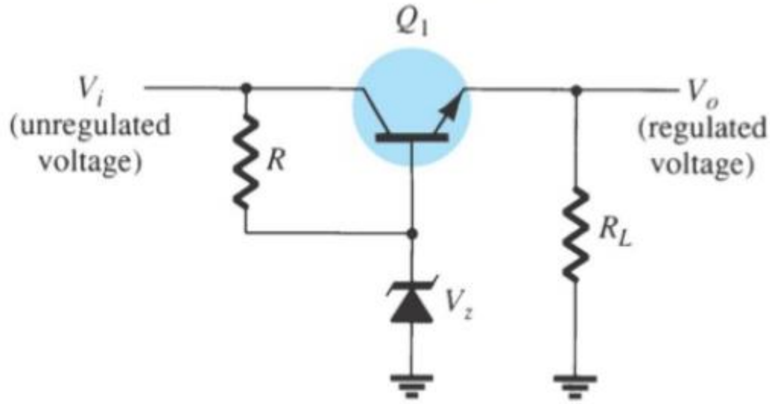


Op-Amp Series Regulator

- The resistor R_1 and R_2 sense a change in the output voltage and provide a feedback voltage.
- The error detector compares the feedback voltage with a Zener diode reference voltage.
- The resulting difference voltage causes the transistor Q_1 controls the conduction to compensate the variation of the output voltage.
- The output voltage will be maintained at a constant value of:

$$V_o = \left(1 + \frac{R_1}{R_2}\right) V_Z$$

Transistor Series Regulator



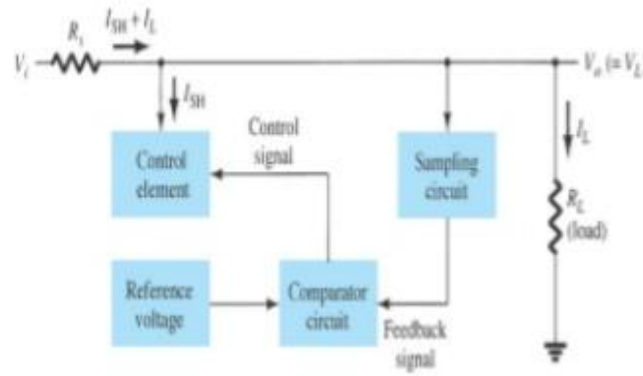
- The transistor Q_1 is the series control element.
- Zener diode provides the reference voltage.
- Since Q_1 is an npn transistor, V_o is found as:

$$V_{BE} = V_Z - V_o$$

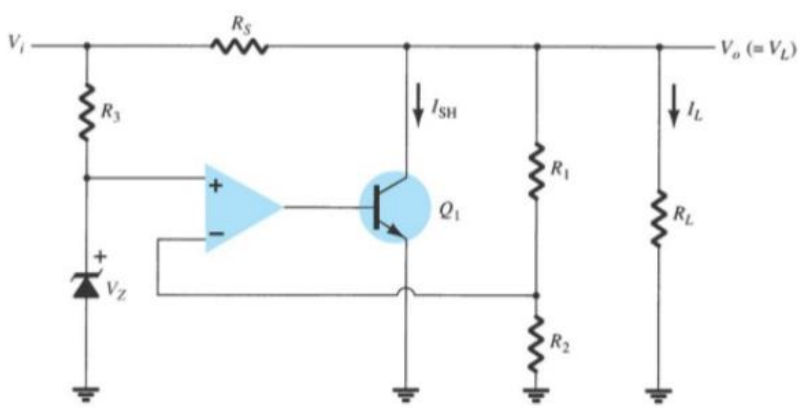
- the response of the pass-transistor to a change in load resistance as follows:
  - If load resistance increases, load voltage also increases.
  - Since the Zener voltage is constant, the increase in V_o causes V_{BE} to decrease.
  - The decrease in V_{BE} reduces conduction through the pass-transistor, so load current decreases.
  - This offsets the increase in load resistance, and a relatively constant load voltage is maintained

Shunt Regulator Circuit

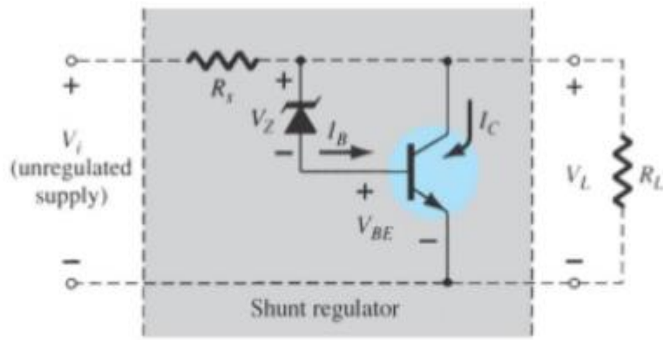
- The unregulated input voltage provides current to the load.
- Some of the current is pulled away by the **control element**.
- If the load voltage tries to change due to a change in the load resistance, the **sampling circuit** provides a feedback signal to a **comparator**.
- The resulting difference voltage then provides a control vary the amount of the current signal to shunted away from the load to maintain the regulated output voltage across the load.



Op-Amp Shunt Regulator



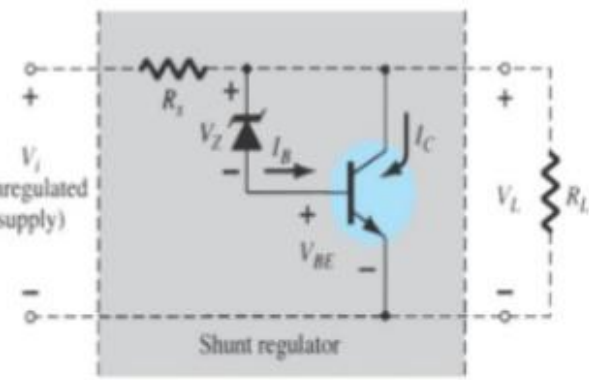
Transistor Shunt Regulator



- The control element is a transistor, in parallel with the load. While, the resistor, R_S, is in series with the load.
- The operation of the transistor shunt regulator is **similar** to that of the transistor series regulator, except that regulation is achieved by **controlling the current through the parallel transistor**

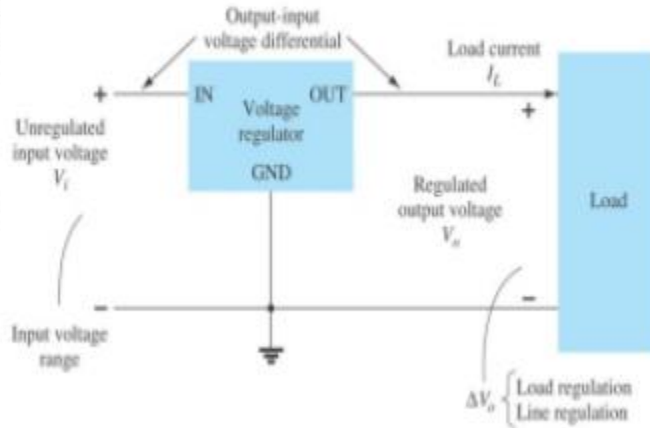
- When the output voltage tries to decrease due to a change in input voltage or load current caused by a change in load resistance, the decrease is sensed by R_1 and R_2
- A feedback voltage obtained from voltage divider R_1 and R_2 is applied to the op-amp's non-inverting input and compared to the Zener voltage to control the drive current to the transistor.
- The current through resistor R_S is thus controlled to drop a voltage across R_S so that the output voltage is maintained.

- The output voltage to the load is: $V_o = V_L = V_Z + V_{BE}$
- voltage across the load is set by the Zener diode voltage and the transistor base-emitter voltage.
- If the load resistance decreases, the load current will be larger at a value of: $I_L = \frac{V_L}{R_L}$
- The increase in load current causes the collector current shunted by the transistor is to be less: $I_C = I_S - I_L$
- The current through R_S: $I_S = \frac{V_i - V_L}{R_S}$
- Resistor R_S drops the unregulated voltage depends on current supplied to load R
- Voltage across the load is set by zener diode and transistor base-emitter voltage.
- If R_L decrease, a reduced driv current to base of Q1 → shunting less collector current.
- Load current, I_L is larger, maintaining the regulated voltage across load.



Switching Regulator

- The switching regulator is a type of regulator circuit which its efficient transfer of power to the load is greater than series and shunt regulators because the transistor is not always conducting.
- The switching regulator passes voltage to the load in pulses, which then filtered to provide a smooth dc voltage.



- The switching regulator is **more efficient** than the linear series or shunt type.
- This type regulator is ideal for high current applications since less power is dissipated.
- Voltage regulation in a switching regulator is achieved by the on and off action limiting the amount of current flow based on the varying line and load conditions.
- With switching regulators 90% efficiencies can be achieved.

IC Voltage Regulators

- Regulation circuits in integrated circuit form are widely used.
- Their operation is no different but they are treated as a single device with associated components.
- These are generally three terminal devices that provide a positive or negative output.
- Some types have variable voltage outputs.
- A typical 7800 series voltage regulator is used for positive voltages.
- The 7900 series are negative voltage regulators.
- These voltage regulators when used with heatsinks can safely produce current values of 1A and greater.
- The capacitors act as line filtration.

- Several types of both linear (series and shunt) and switching regulators are available in integrated circuit (IC) form.
- Single IC regulators contain the circuitry for:

(1) reference source
(2) comparator amplifier
(3) control device
(4) overload protection

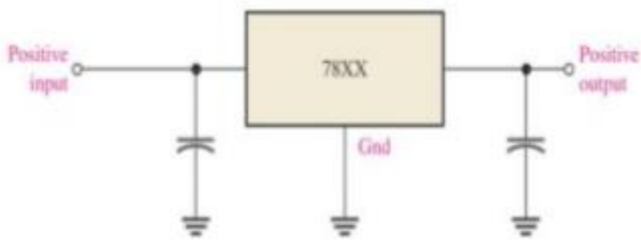
- Generally, the linear regulators are three-terminal devices that provides either positive or negative output voltages that can be either fixed or adjustable.

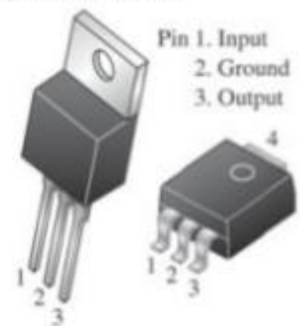
Fixed Voltage Regulator

- The fixed voltage regulator has an unregulated dc input voltage V_i applied to one input terminal, a regulated output dc voltage V_o from a second terminal, and the third terminal connected to ground.

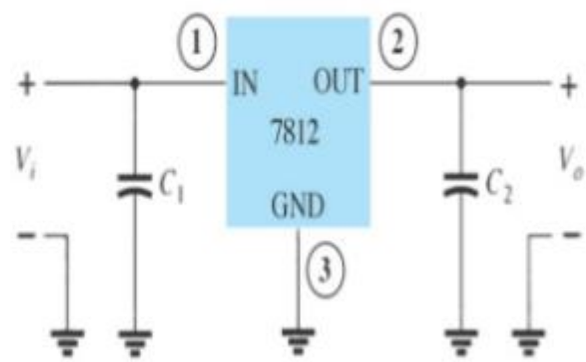
Fixed-Positive Voltage Regulator

- The series 78XX regulators are the three-terminal devices that provide a fixed positive output voltage.



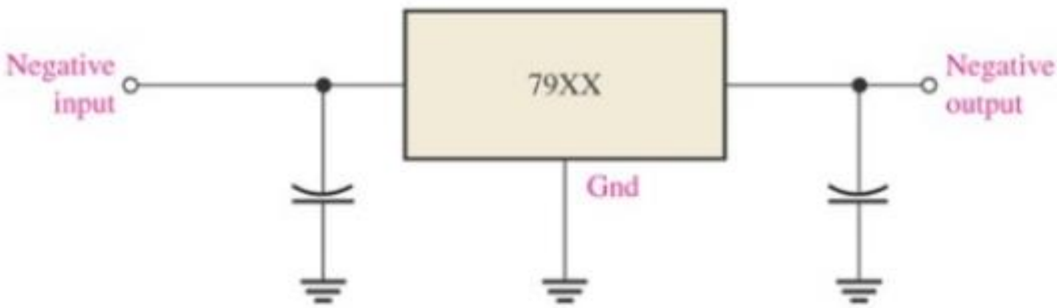


- An unregulated input voltage V_i is filtered by a capacitor C_1 and connected to the IC's IN terminal.
- The IC's OUT terminal provides a regulated +12 V, which is filtered by capacitor C_2.
- The third IC terminal is connected to ground (GND)



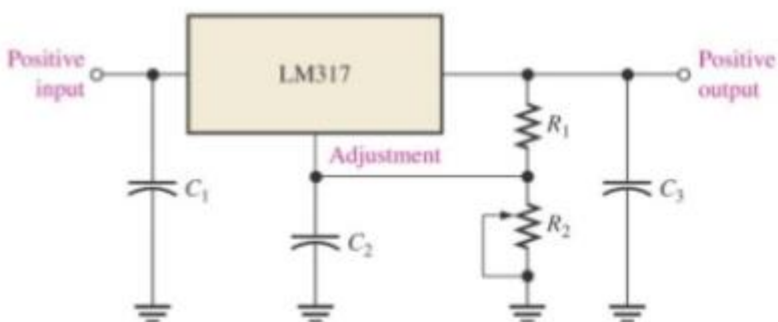
Fixed-Negative Voltage Regulator

- The series 79XX regulators are the three-terminal IC regulators that provide a fixed negative output voltage.
- This series has the same features and characteristics as the series 78XX regulators except the pin numbers are different.



Adjustable-Voltage Regulator

- Voltage regulators are also available in circuit configurations that allow to set the output voltage to a desired regulated value.
- The LM317 is an example of an adjustable-voltage regulator, can be operated over the range of voltage from 1.2 to 37 V.



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SCHOOL OF MECHANICAL ENGINEERING

DEPARTMENT OF MECHATRONICS ENGINEERING

UNIT – V - Adaptive Control System – SIC1612

UNIT 5

ADAPTIVE PROTECTION

Need of Adaptive Protection in the system - Techniques for adaptive strategies in distance protection - Synchro-phasor based adaptive protection schemes - protection schemes - SCADA based protection systems - FTA - Testing of Relays.

Adaptive Protection

The use of adjustable protective relay settings (e.g., current, voltage, feeders, and equipment) that can change in real time based on signals from local sensors or a central control system. This is particularly useful for feeder transfers and two-way power flow issues associated with high Distributed Energy Resource (DER) penetration.

For Reference https://www.researchgate.net/publication/327819009_Overview_of_Adaptive_Protection_System_for_Modern_Power_Systems

Electromechanical relay has been used for more than 60 years to provide protection for the power. These types of relays have longer lifespan, needs low maintenance and reliable. However static relay has shown higher usage demand from 1960 onwards. It provides lower burden, improves the performance characteristic, self-monitoring and many more. For protection, one of these options can be used. However, it should be consistent for the whole circuit. Electromechanical and static relays are examples of analogue relay. They do not determine the exact location of the fault. Instead, will establish a zone of protection which the relay will operate. Analogue relays models are not easy to make precisely. The main reason has been the lack of detailed design data on which to base the model and the difficulties involved such as fitting a digital model to a nonlinear analogue device. These analogue protective relays are offline and constant when operating. This setting method cannot adapt to the changes of topology structure and operation mode. It is because the relay cannot get the best protection effect. The modern relays are digital and have an automatic setting. These relays are based on microprocessors operating in real time. They can adapt to their settings. They do not need to duplicate the conventual relay characteristic. Instead it can calculate the exact location of a fault and arc. Therefore, there will be almost zero incorrect operations. These types of relays are used by adaptive protection. By tallying and changing the information online, this relay can adapt to the adjustment of the topology architecture, functioning method and the type of the fault occurring in the system. Based on the functions and information used, Adaptive Protection scheme can be categorized as two separate areas; adaptive protection device and adaptive protection system. The device, in general, uses actual data and is able to adapt to the changes of the processing mode for certain zones. The integrated communication network shares the information throughout the system and adjust to the changes of operation mode for large areas. The key importance of a protection system should be reliable (operate when required), secure (not to be operated unnecessarily), selective (only a minimum number of fault interrupting devices required should operate), and fast (isolation of fault). In addition, backup protection should be cleared when any fault upon failure of the protective equipment happened in the primary protection system.

OVERVIEW PROTECTION SYSTEM

Protection system is one of the key stages to take note when designing a good power system. The relays are designed where it finds the fault and quickly isolates the fault area without harming the other parts of the system. Therefore, the information helps the industry to evade of damaging the equipment with huge losses in the manufacturing process. This is due to the overload or fault of the system. This further helps to isolate and replace faulty equipment, minimizes the property losses and safety of the people. There are some criteria to be followed throughout when choosing a relay protection. The main key is that, it should isolate any fault very quickly, at the same time neighboring areas should work smoothly. The relay must be affordable and should able to achieve high efficiency of the power system safety. It should also be reliable and support high-speed operation.

Zone Protection

The most basic type of protection for any type of system is the zone protection. It acts as a primary and/or backup protection. When a fault happens, the first line of defense would be the primary protection. The backup protections occur when it fails to isolate the fault primarily, and by re-tripping the circuit breaker. Another option is tripping the circuit breakers of the neighboring areas to the fault. Backup Protections can be either Local or Remote based on their location in the system. Local backup protections are based on the same zone as the fault happened. The circuit breakers of the primary or the nearby zones would trip when a fault occurs. The remote backup protection is pre-defined, and the circuit breakers will only trip when a fault occurs in that zone. Overlapping neighboring zones is one of the standard conditions to maintain the power system. This method safeguards and protects the entire system. However, there are consequences as both overlap zones will be isolated when a fault occurs. The system shall be designed in such a way to minimize these overlapping zones as a solution. The following diagram shows how circuit breakers are connected in the power system.

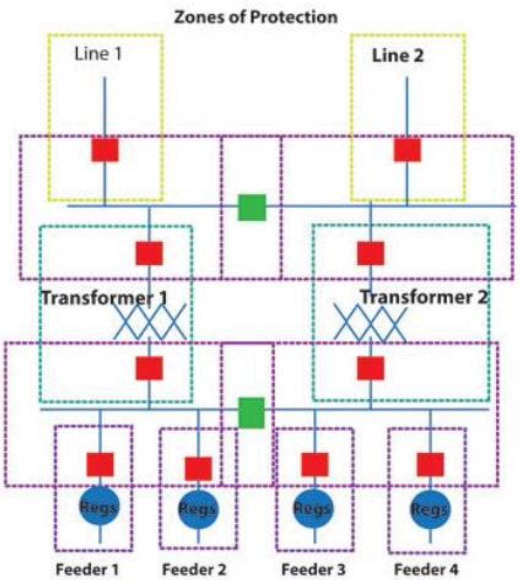


Fig : Overall structure of general protection system

Overcurrent Protection

The Overcurrent Protection is simple to use and is the mostly used protection scenario in the radical distribution.

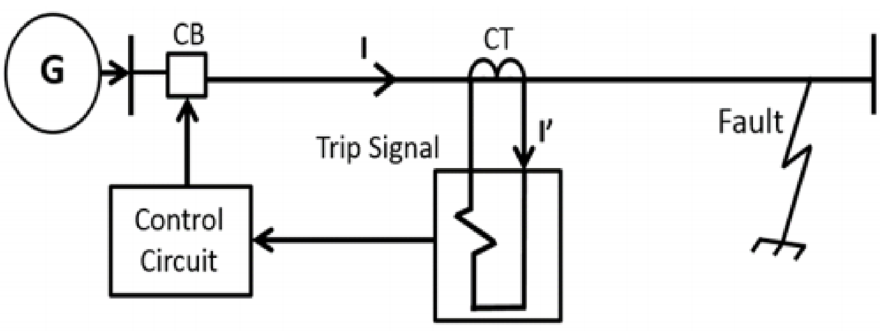


Fig 2: Representation of overcurrent relay

Where, I' can be defined as the generated current from the secondary side of the CT (Current Transformer) and Ipickup is a standard rating of the relay setting, also known as the pick-up current or the threshold current. The following the principle for overcurrent protection: Normal operation: I' < Ipickup Short Circuit fault: I' > Ipickup There is no trip signal and the circuit breaker is closed as shown in the formula for “Normal operation”. However, the circuit breaker will be tripped and isolate the fault, when the secondary current (I’) coming from transformer is greater than pick-up current (Ipickup). Two fundamental parameters, the pickup current threshold and the time-dial setting of the relay shall be selected properly to protect the system. Overcurrent relays are the most commonly-used protective relay type. Overcurrent relay has two types of protection; instantaneous overcurrent relay (Relay-50) and time-overcurrent relay (Relay-51). The characteristics of the Relay-50 is that it operates as soon as the current gets higher than a predetermined value when there is no intentional time delay is set. However, there could be an inherent time delay in an order of milliseconds based on the manufacturer’s data [9]. In Relay-51, operating time is inversely changed with the current. There are three commonly used characteristics which is inverse, very inverse and extremely inverse. It is possible to have combined Relay-50 and Relay-51 in a System and is referred to as a Relay 50/51.

Protection device coordination:

The basic role of the coordination technique is to correctly choose the information and parameters for the relays on the distribution side of the power system. I_{pickup} and the time delays define the thresholds, letting the system to disregard transient overloads and allowing it to operate within norms up to the closest to a fault or breakdown. Without harming the sensitivity, the protection device coordination needs to obtain the maximum selectivity.

Time Current Characteristic (TCC) curve tells how fast a protection device triggers when a fault occurs. There is no characteristics for high voltage circuit breaker under time current curve. There is a directional overcurrent relay being used with a directional element added to it. Under the TCC, the low voltage circuit breaker has its own characteristic.

Directional Overcurrent Protection Relay 67 is used for Directional Overcurrent Protections. The concept is like the overcurrent protection. However, for directional overcurrent can be flown in either forward or reverse direction. This kind of protection is mainly used in parallel lines. For this type of protection there are three types of parameters needed, which are voltage, current and the phase angle between voltage and current. Relay-67 is often used as the intelligent electronic device to determine the direction, the fault current is flowing and to trip the appropriate devices accordingly. The residual voltage is three times the zero-sequence voltage drop on the source impedance during a ground fault. The phasor voltage is balanced when the residual voltage is zero. The values must be calculated precisely in order to have the exact directional protection.

Differential Protection

The differential transformer protection is denoted by 87T. It is a fast, selective method of protection against short circuit in transformer. The concept it follows is the Kirchhoff's Law. This protection mainly works for internal protection of transformers where differential current is greater than zero. The differential protection does not support external faults and overloading of large motors, generators, lines, cables, bus, etc., but only support and protect them from internal faults. An overcurrent relays shall be used should there be a requirement to protect such systems from external faults and overloads.

Distance Protection

The distance relay is denoted by (Device 21). It is operated by using voltage and current to determine if a fault is in the protection zone of the relay. These types of relay can detect phase faults as well as ground faults. The characteristic of these relays can be seen in a R-X diagram. The following are some basic characteristics of the relay.

1) Impedance: The impedance characteristic does not take into account the phase angle between the voltage and the current applied to it. In the R-X plane impedance characteristics shown as a circle with its center at the origin. The relay operates when the measured impedance is less than the settings.

2) Reactance: It only measures the reactive component of the impedance. The characteristic of the impedance relay in the R-X plane is a straight line parallel to the R axis.

3) Quadrilateral: This characteristic can be achieved by combining directional and reactance characteristics with two resistive reach blind characteristics.

4) Mho: The characteristic of Mho relay in the R-X plane is a circle whose circumference passes through the origin. This type of relay operates when measured impedance falls within the circle.

CHALLENGES IN PROTECTION

In recent years, electric power sources have been expanded and the large scale renewable energy deployments, which are environmental friendly and avoid any affect to the climate changes, are key to this energy transition. To find solutions for those problems, Europeans and other countries suggested and came up with the idea of smart grid. This is now being the key concept in the national power strategy. These days smart grid has taken the name of the next generation of the power grid. Smart grid uses digital technology to supply electricity and has two-way communication. It helps to improve various things. They are reliable, reduces the peak demand and increase the energy efficiency. This will benefit the environment along with the efficiency. Analysis and Isolation is the most identified factor when designing a modern power system. It should isolate fully when a fault occurs in the grid. Also, it should quickly isolate any affected zones in the main grid or other parts in the grid for the safety of the load. Fig 3: Time Current Characteristics (TCC) Curve The smart protection system is the subsystem of the smart grid. It provides advanced grid reliability analysis, failure protection, security and privacy protection services.

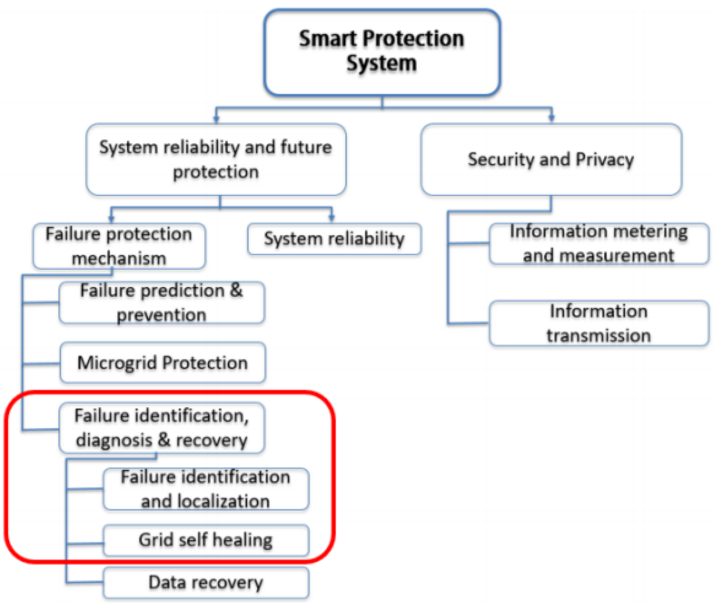


Fig 4: Smart Protection System

Self-Healing

In the principle of self-healing protection, the circuit breaker opens automatically without any human intervention, when a fault happens and is intelligent enough to self-adjust quickly to maintain the normal operation conditions. The circuit breakers are closed for the neighboring areas and will not interrupt the system. It is one of the smart way of providing protection when a fault occurs. To achieve self-healing in a power grid, the system should have sensors, automated controls, and advanced software that uses real-time distribution of data to detect, isolate faults and to reconfigure the distribution network to minimize the power outage and customer impact. Self-healing, supported by these control electronics and software, intelligently does reconfiguration, load shedding, and also controls the output power of connected generators. System reliability is one of the key objectives in self-healing. This can be done by rearranging the circuit breakers and relays. To quickly isolate the fault, reclosers are mounted on the distribution network. They can be integrated with other alternate sources to restore services to as many customers as possible. Many constraints due to non-linear optimization can be seen as one of the deadlocks in Self-healing. The solutions using modern digital algorithms are underway using techniques such as artificial intelligence.

ADAPTIVE PROTECTION SCHEME

Adaptive protection has been established since the 1980s. It was enabled by the increase of the computer-based relaying. This enabled to change the characteristic of the relay setting. The evolving networks create the need for adaptive protection such as existing relay settings and protection methods may become inappropriate. The idea behind the adaptive protection defines the ability of the protection system to adapt to the current operating condition of the power system. This technique is more relevant than modern digital relays because it has automatic settings. The main objective of the adaptive protection scheme is to change the relay setting to match with the main power system conditions. Under the adaptive protective scheme, there are four main elements. They are hardware, communication and control, software and human factors. The hardware refers to the digital relays. Communication and control refers to the computational systems used to monitor the relays and coordinate the changes needed in the face of changing network conditions. The software refers to algorithms controlling the systems use to coordinate relays.

Overall structure of the adaptive protection system

The structure of the system offers its overall frame and define its functions and correlations of its elements. Each module in the system would achieve their parts and interact with each other at the same time. The following diagram Fig 5. is the representation of the overall structure of adaptive protection system of power supply and distribution system.

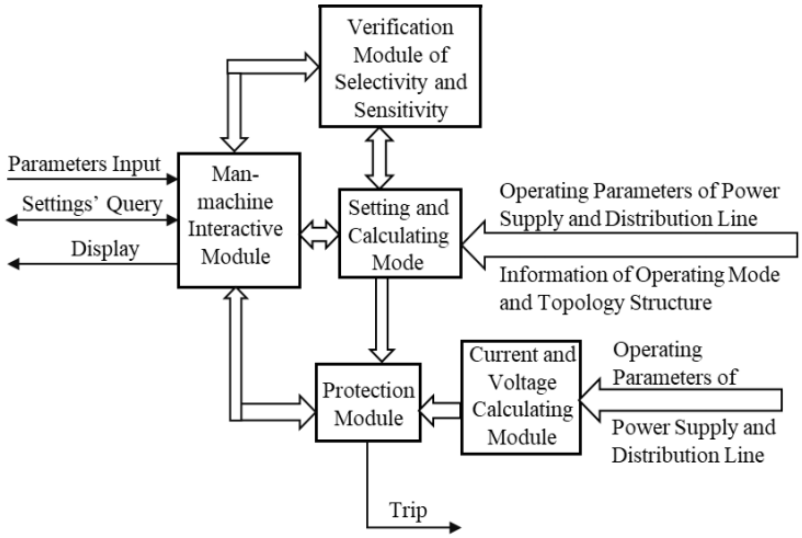


Fig 5: Adaptive protection of power supply and distribution system

The following are the main functions of the modules:

1) Man-machine Interactive Module: All main operating parameters, information of operating mode and topology structure, operating parameters of voltage, current and the respective protection methodologies, verification techniques of selectivity and their sensitivities, etc., are being fed and queried while it displays and provides the scenarios of the adaptive protection device of the power supply and the distribution line.

2) Verification module of selectivity and sensitivity: It confirms whether it is reasonable for the setting of the device and checks for both selectivity and sensitivity. The selectivity function confirms whether the circuit breaker will trip or not if a fault happens at the end of the protection scope.

3) Verification Setting and Calculating Module: It is one of the key systems. It checks whether things change according to the information given by the SCADA system and operating parameters of power supply and distributing line.

4) Current and Voltage Calculating Module: This module, accurately calculates the voltage and current of the power supply and the distribution line. The inputs are fed to the Protection Module.

5) Protection Module: Receives analyses the inputs from Setting and Calculating Module and from the Current and Voltage Calculating Module to determine whether the tripping condition is satisfied or not. This also feds the information to the Man Machine Interactive Module about the

line details, fault type, time of the fault occurs, etc., to display if the adaptive protection is trips, after satisfying the pre-defined conditions.

RECOMMENDATION FOR FUTURE POWER SYSTEM PROTECTION

We are in the era of Smart Solutions and the prediction is that the number of smart cities will reach 600 worldwide by 2020. Digital technologies in the Smart Cities could become the engine of economic progress, and Smart Grids, without a doubt, could be one of them. While opening new trends and opportunities this may also generate many physical, social, behavioral, economic, and infrastructural challenges. When addressing these challenges in implementing adaptive protection solutions in modern power systems, two scenarios are explained in detail in following paragraphs.

Software for adaptive protection system

Adaptive relaying is a new viewpoint in protecting electric power systems. It operates the continuously changing status of the power system as the basis for on-line adjustment. It is required because fault current and load alter with time. The reason for that is the generation and topology alter. In order for this to occurs, the information in the relay needs to be altered. Therefore, time delay can be reduced and maintaining the coordinate margins. The following paragraphs will discuss about the different types of software for adaptive protection system.

1) Relay modeling software:

   Off-line mode is where relay's features are being chosen from. The different setting characteristics are stored in Time Multiplier Setting (TMS) of the adaptive system. The relay's characteristics at a selected TMS should be stored in the relay memory. If the relays are fixed at different places in the distribution system, it might need to implement different sets of parameters. The standard product characteristics are available on-line and can be used whenever required. A significant role is being played by the pick-up value of the current relay (Ipickup) and formulates the trip decision logic along with the TSM data.

2) Relay co-ordination software:

   The software studies the altering of the system and for the setting of the relay, it will find the most suitable one. This software has four packages which is topology detection, state estimator, fault analysis and relay setting program

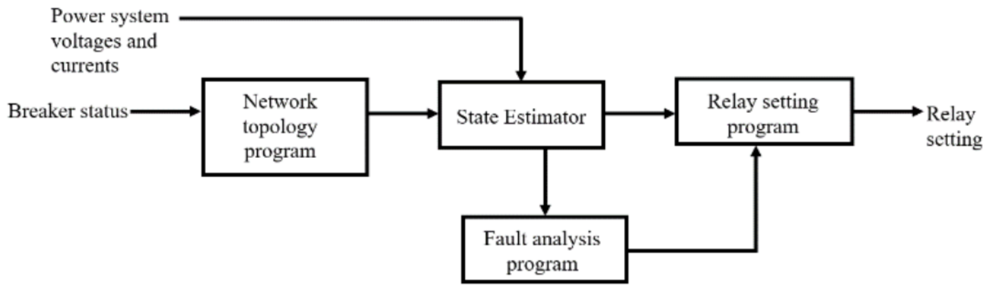


Fig 6: Block diagram of relay co-ordination software

3) Relay communication software:

   The main role of adaptive relay system is the communication. It interchanges data between station computer and main computer There are three types of packages in communication software. The first package support various types of relays processors to interact with each other. The second package support the station computers to interact with the relay processors. The last package support interaction between the main computer and station computers.

Functioning of adaptive protection system

Adaptive protection systems function in two modes; changes of system during normal operation condition and the operations during faults and transients.

1) Changes of system operating conditions: In the first mode, the relay would test the substation bus voltages and the circuit currents. This information will then be translated to current and voltage phasor before transporting to the substation computer. The changes that happen subsequently will be found by the system. It would be known by this data. The main computer will receive any data which has been altered from the original. Then the system starts computing a state estimation study and a fault analysis study. New relay settings will be generated and transported back to the station computers to be restored in the individual relays. It will then be communicated back to the individual relays.

2) Operation during faults and transients: In this second mode of operation, a form of look-up table based on the relay characteristics is used when deciding the I_{pickup} and trip decision logic. It will always monitor the circuit. If an abnormal condition happens, it will issue a command to the necessary circuit breaker to trip and all the circuit configuration changes will be transported to the main computer for calculating the new relay setting. It will then be communicated back to the individual relays.

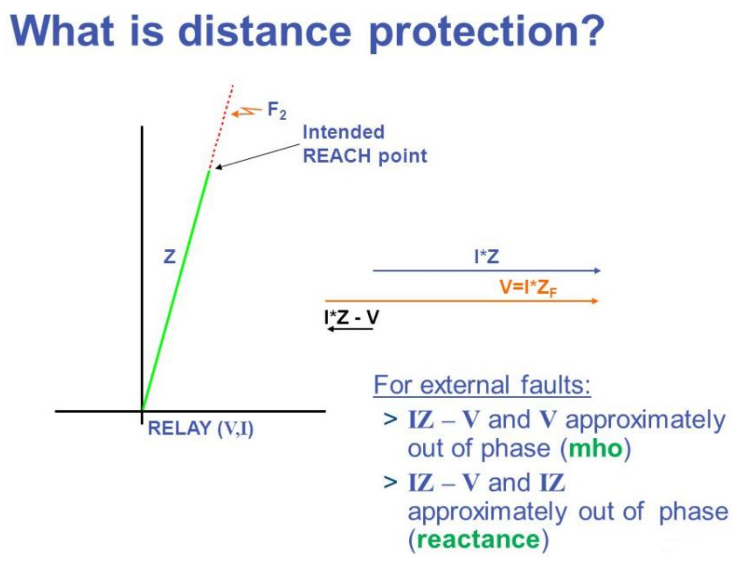
Distance Relaying
Motivation

- Changing the fault condition, particularly in the presence of DC offset in current waveform, as well as network changes lead to problems of underreach or overreach.
- Conventional schemes suffer from their slow response.

AI Applications in Distance Relaying

- Using ANN schemes with samples of V&I measured locally, while training ANN with faults inside and outside the protection zone.
- Same approach but after pre-processing to get fundamental of V&I through half cycle DFT filter.
- Combining conventional with AI: using ANN to estimate line impedance based on V&I samples so as to improve the speed of differential equation based algorithm.

- Pattern Recognition is used to establish the operating characteristics of zone-I. The impedance plane is partitioned into 2 parts: normal and fault. Pre-classified records are used for training.
- Application of adaptive distance relay using ANN,where the tripping impedance is adapted under varying operating conditions. Local measurements of V&I are used to estimate the power system condition.



Distance Protection Relays Working Principle:

In last study we have discussed about only current or voltage based relay. Now we are going to discuss about current and voltage based relay. These relays are called as distance protection relays. The relay operation is purely depending upon the magnitude of the circuit current and voltage, typically the ratio of the circuit to be protected is calculated. The ratio of Voltage to current is called impedance. Here the prefix word distance mentions that impedance is nothing but an electrical measurement of distance along a transmission line. The relay measures the ratio of voltage and current. The ratio is less than a predetermined value, the relay trips the circuit breaker. The distance protection relay is also called as ratio relay.

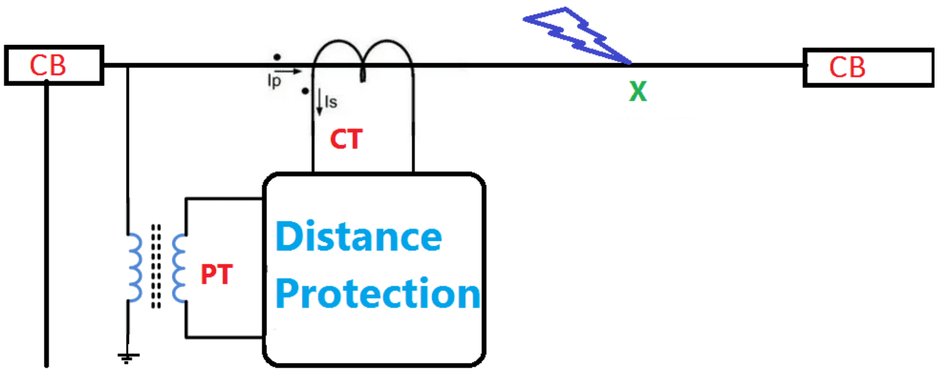
Dependent on the ratio of V and I the distance relays are classified into three types

1. Impedance (Z) relay.
2. Reactance relay (X)
3. Admittance (Y) or Mho relay

Impedance Relay

The impedance relay works based on the circuit quantities such as voltage and current. In this relay, there are two elements, the one produces a torque proportional to current while the other produces a torque proportional to voltage. The torque produced by the current element is equalized by the torque produced by the voltage element. The current element produces operating torque and voltage element produce the opposite torque to the current element. In other words, the torque produced by the voltage element is said to be negative torque.

Voltage reference is taken from the potential transformer and the current reference is taken from the current transformer. The section AB of the line is protected zone which is impedance of line. Under normal conditions, the ratio of voltage V and current I is constant which is denoted as Z. The relay is inoperative under this condition. [wp_ad_camp_1]



Distance Protection Relay Working

When the fault occurs at point X in the protected zone then the voltage drops while current increases. Thus the ratio of V/I. the impedance reduces. This is the impedance of line between relay located and the faulty point X. So when the impedance reduces than its predetermined value, the distance protection trips circuit breaker.

Torque Equation

Consider The circuit current I, Voltage V, T operating torque. The positive torque is directly proportional to I^2 and the negative torque is directly proportional to the voltage element V^2.

Let control spring effect produces a constant torque of $-K_3$, Hence the torque equation becomes,

$$T = K_1 * I^2 - K_2 V^2 - K_3$$

where K1. K2, are the constants,

At the balance point, when the relay is on the verge of operating, the net torque is zero hence we can write,

$$0 = K_1 * I^2 - K_2V^2 - K_3$$

$$K_2V^2 = K_1 * I^2 - K_3$$

Divide By K_2 I_2 on both sides..

$$\frac{V^2}{I^2} = \frac{K_1}{K_2} - \frac{K_3}{K_2 * I^2}$$

As We Know The ratio of voltage to current is called impedance. It is denoted by Z

$$Z = \frac{V}{I}$$

Apply it on the above equation

$$Z = \sqrt{\left(\frac{K_1}{K_2} - \frac{K_3}{K_2 * I^2}\right)}$$

Neglect the spring constant as it is absence in practical case. Hence K_3=0

$$Z = \sqrt{\frac{K_1}{K_2}}$$

Hence the ratio of V/I is constant at normal operating condition.

How Distance Protection Detects the Fault location:

From the above V/I ratio, for the particular fault the impedance is constant. But The value of the ratio changes according to the fault location changes. Also the fault is nearer to relay, this ratio of the V/I will be low and as fault position moves away from the relay the ratio becomes higher and higher. So it can be installed to operate for particular location to be protected and After conducting relay adjustments for the particular location, it is inoperative beyond that section.

Protection of Transmission lines (Distance Protection)

❖ As the length of electrical transmission line is generally long enough and it runs through open atmosphere, the probability of occurring fault in electrical power transmission line is much higher than that of transformers and alternators .

❖ That is why a transmission line requires much more protective schemes than a transformer and an alternator.

Features of protection of transmission line

1. During fault, the only circuit breaker closest to the fault point should be tripped.

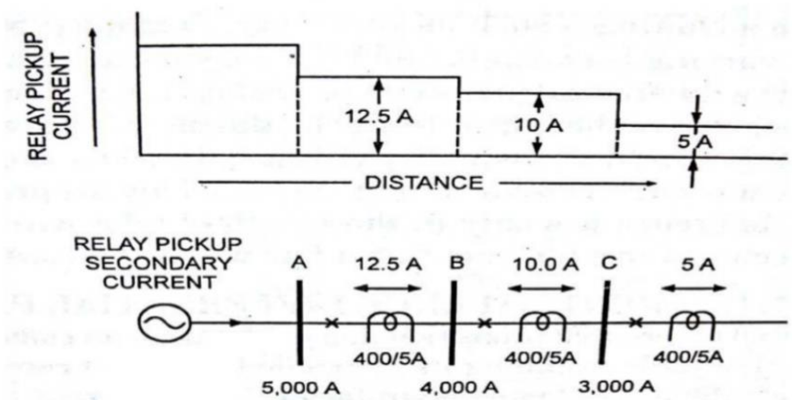
1. If the circuit breaker closest the faulty point, fails to trip the circuit breaker just next to this breaker will trip as back up.

2. The operating time of relay associated with protection of line should be as minimum as possible in order to prevent unnecessary tripping of circuit breakers associated with other healthy parts of power system.

The main methods of transmission line protection

1. Time graded over current protection
2. Current graded over current protection.
3. Distance protection.
4. Differential protection
5. Carrier current protection

Current graded protection



**The short ckt current along the length of protected ckt decreases with increase in distance between supply end and fault point

Difficulties in current graded protection

1. The relay can not discriminate between the fault in the next section and the end of first section.

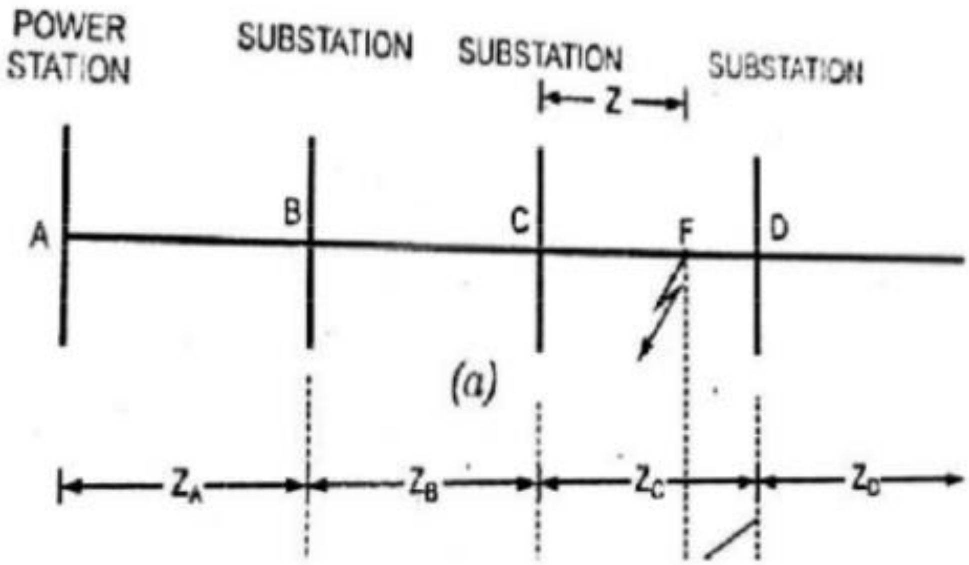
***Hence for discrimination the relays are set to protect only part of the line, usually 80%*

2. fault currents are different for different types of fault so difficulty experienced in relay setting

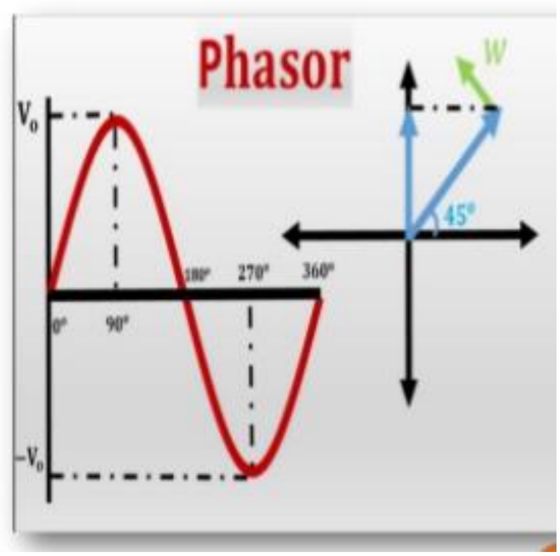
3. For the ring mains, parallel feeders ,where power can flow to fault from either direction , a system without directional control is not suited.

For this reason current grading alone can not be employed

Distance protection of transmission line



- **Phasor is a quantity with magnitude and phase (with respect to a reference)** that is used to represent a sinusoidal signal.
- Here the **phase or phase angle is the distance between the signal's sinusoidal peak and a specified reference and is expressed using an angular measure.**
- Here, the **reference is a fixed point in time (such as time = 0).**
- The phasor magnitude is related to the **amplitude of the sinusoidal signal**.



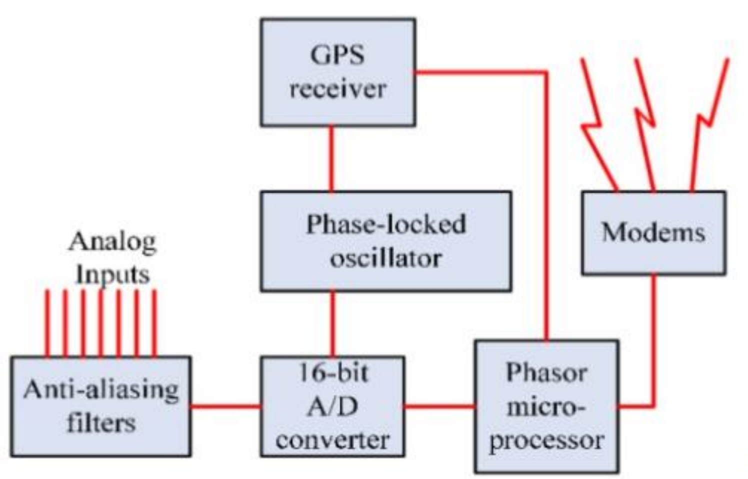
- A **phasor measurement unit** (PMU) is a device used **to estimate the magnitude and phase angle of an electrical phasor quantity** (such as voltage or current) in the electric grid using a common time source for synchronization.
- **Time synchronization is usually provided by GPS** and allows synchronized real-time measurements of multiple remote points on the grid.
- **PMUs are capable of capturing samples from a waveform in quick succession** and reconstructing the phasor quantity, made up of an angle measurement and a magnitude measurement.
- The resulting measurement is known as a ***synchrophasor***. These time synchronized measurements are important because if the grid's supply and demand are not perfectly matched, frequency imbalances can cause stress on the grid, which is a potential cause for power outages.
- PMUs can also be **used to measure the frequency** in the power grid.
- A typical commercial PMU can report measurements with very high temporal resolution in the order of **30-60 measurements per second**. This helps engineers in analyzing dynamic events in the grid which is not possible with traditional **SCADA measurements** that generate one measurement every **2 or 4 seconds.**
- Therefore, PMUs equip utilities **with enhanced monitoring and control capabilities** and are considered to be one of the most important measuring devices in the future of power systems.
- A PMU can be a dedicated device, or the PMU **function can be incorporated into a protective relay** or other device.

- PMU an essential component of Smart Grids.
- It **provides Synchrophasor data**
- **Reports Magnitude, Phase and Frequency** of an AC waveform
- **Makes the grid observable** due to high reporting rates
- **Preventive actions** can be taken such as black outs

THE MAIN COMPONENTS OF PMU

- Analog Inputs
- GPS receiver
- Phase locked oscillator
- A/D converter
- Anti-aliasing filters
- Phasor micro-processor
- Modem

BLOCK DIAGRAM OF PMU



- **Current and potential transformers** are employed at substation for measurement of voltage and current.
- **The analog inputs to the PMU are the voltages and currents** obtained from the secondary winding of potential and current transformers.

- Anti-aliasing filter is an analog low pass filter which is **used to filter out those components from the actual signal whose frequencies are greater than or equal to half of nyquist rate to get the sampled waveform.**
- Nyquist rate is equal to twice the highest frequency component of input analog signal.
- If anti aliasing filters are not used, **error will be introduced in the estimated phasor**

- Phase lock oscillator along with Global Positioning System reference source **provides the needed high speed synchronized sampling.**
- Global Positioning System (GPS) is a satellite-based system for **providing position and time.**

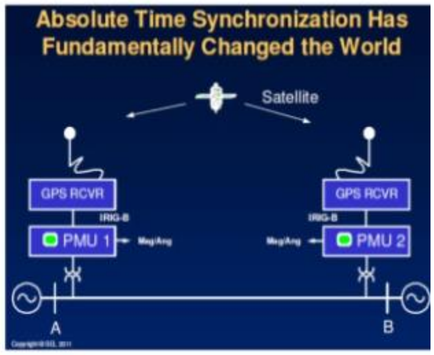
- It **converts the analog signal to the digital signal.**
- Quantization of the input involves in ADC that introduces a small amount of error.
- The output of ADC is a sequence of digital values that convert a continuous time and amplitude analog signal to a discrete time and discrete amplitude signal.
- It is therefore required to define the rate at which new digital values are sampled from the analog signal.
- The rate of new values at which digital values are sampled is called the sampling rate of the converter.

- The synchronized time is given by GPS **uses the high accuracy clock from satellite technology.**
- Without GPS **providing the synchronized time**, it is hard to monitor whole grid at the same time.
- The GPS satellites **provide a very accurate time synchronization signal**, available, via an antenna input, throughout the power system. This means that that voltage and current recordings from different substations can be directly displayed on the same time axis and in the same phasor diagram.
- A device that **modulates an analog carrier signal and encodes digital information from the signal and can also demodulate the signal to decode the transmitted information from signal** is called modem.
- The objective of modem is to **produce a signal that can be transmitted and decoded to make a replica of the original digital data.**
- Modem can be used with no means of transmitting analog signals

- The microprocessor **calculates positive-sequence estimates of all the current and voltage signals using the DFT techniques.**
- **Certain other estimates of interest are frequency and rate of change of frequency measured** locally, and these also are included in the output of the PMU.
- The timestamp is created from two of the signals derived from the GPS receiver.
- The time-stamp identifies the identity of the "universal time coordinated (UTC) second and the instant defining the boundary of one of the power frequency periods.

SYNCHROPHASOR

- A synchrophasor is a phasor measurement with respect to an absolute time reference.
- With this measurement we can determine the absolute phase relationship between phase quantities at different locations on the power system.



FEATURES OF PMUs

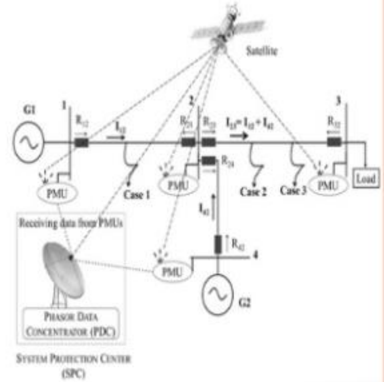
- PMUs are Measures 50/60 Hz AC waveforms (voltage and current) typically at a rate of 48 samples per cycle.
- PMUs are then computed using DFT-like algorithms, and time stamped with a GPS.
- The resultant time tagged PMUs can be transmitted to a local or remote receiver at rates up to 60 samples per cycle.

APPLICATION OF PMU IN POWER SYSTEM

1. Adaptive relaying
2. Instability prediction
3. State estimation
4. Improved control
5. Fault recording
6. Disturbance recording
7. Transmission and generation modeling verification
8. Wide area Protection
9. Fault location

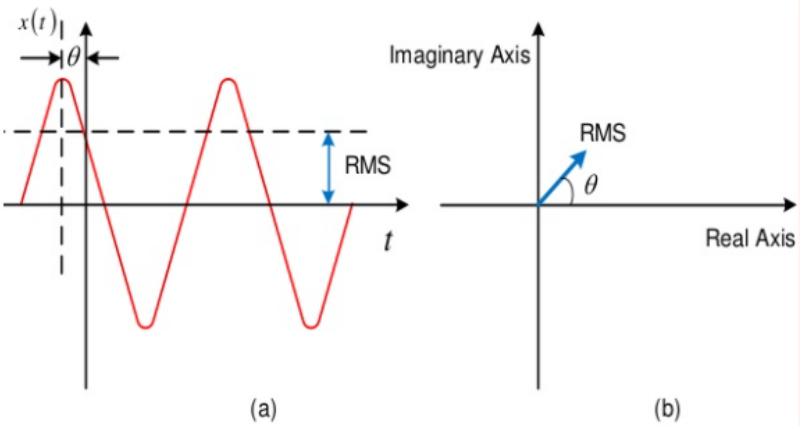
Adaptive Relaying

Adaptive relaying is a protection philosophy which permits and seeks to make adjustments in various protection functions in order to make them more tuned to prevailing power system conditions



Phasor Measuremnet Techniques

- A pure sinusoid quantity given by $x(t) = X_m\cos(\omega t + \theta)$ and its phasor representation $X = (X_m/\sqrt{2})e^{j\theta} = (X_m/\sqrt{2})(cos\theta + jsin\theta)$ are illustrated in Figure. The aim of phasor estimation technique is just to **acquire the phasor representation**.
- Samples of waveform data are collected over a data window which is normally one period of the fundamental frequency of the power system. In early days a sampling rate of 12 times a cycle (720 Hz for the 60 Hz system) was commonly used. Much higher sampling rates are currently used in commercial PMUs.



A sinusoid and its representation as a phasor

SCADA

SCADA stands for supervisory control and data acquisition, a term which describes the basic functions of a SCADA system. Companies use SCADA systems to control equipment across their sites and to collect and record data about their operations.

SCADA typically comes in a combination of software and hardware elements, such as programmable logic controllers (PLCs) and remote terminal units (RTUs). Data acquisition starts with PLCs and RTUs, which communicate with plant floor equipment such as factory machinery and sensors. Data gathered from the equipment is then sent to the next level, such as a control room, where operators can supervise the PLC and RTU controls using human-machine interfaces (HMIs). HMIs are an important element of SCADA systems. They are the screens that operators use to communicate with the SCADA system.

Using SCADA systems, organizations can control their industrial processes either locally or remotely and directly interact with pieces of equipment, such as motors, pumps and sensors, across the board from a central location. Sometimes, these systems can control equipment automatically based on incoming data. SCADA systems also enable organizations to monitor and report their processes based on real-time data and archive the data for subsequent processing and evaluation.

Applications of SCADA

Organizations can use SCADA systems to:

- Control processes locally or remotely
- Interact with devices through HMI software
- Collect, monitor and process data
- Log events and data

These functions give companies enhanced visibility into their processes. The data they collect enables them to see how their machinery is functioning in real-time and also view long-term trends to identify improvement opportunities. Based on this data, operators can then adjust how their equipment runs using SCADA-enabled controls. They can make changes either remotely or on-site and can adjust operations on the level of entire facilities, individual processes or just particular machines.

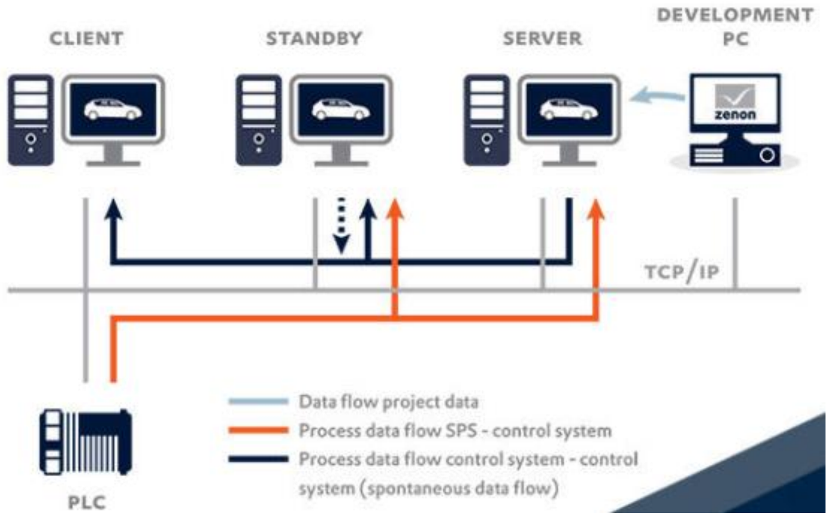
SCADA systems also enable organizations to use their data to improve efficiency, inform decision-making and enhance communication to help prevent downtime. To get the most benefit from your data, which you collect from various sources, you need to store it centrally in a SCADA system. A well-integrated SCADA software can combine data from numerous sources, process it and then send it to other systems in various formats.

Advanced SCADA software can create complete and custom reports. Your equipment may also be able to react automatically to the information in these reports. In a quality management application, for example, the system may trigger an alarm if a report indicates that a batch of products is defective. In energy management, a system may reduce the power consumption of certain machinery or systems if a load peak is forecasted.

Through functions such as these, SCADA systems can save organizations significant amounts of time and money. They can help companies increase the efficiency of their operations, reduce downtime, ensure product quality and much more.

SCADA systems can range from relatively simple to massive and complex, depending on the organization using them and the applications in which they're used.

A basic SCADA network



SCADA systems are important for organizations both large and small across a wide variety of industries, including:

- Energy and infrastructure
- Food and beverage
- Pharmaceutical
- Automotive
- Water and wastewater
- Transportation
- Building
- Cross-industry applications

For a vast range of sectors and organizations, SCADA systems play a central role in how companies control their operations and use their operational data to make better decisions.

Benefits of using SCADA software

Using SCADA software provides numerous benefits to businesses, and zenon helps companies make the most of those benefits. Some of these advantages include:

- **Easier engineering:** An advanced SCADA application such as zenon provides easy-to-locate tools, wizards, graphic templates and other pre-configured elements, so engineers can create automation projects and set parameters quickly, even if they don't have programming experience. In addition, you can also easily maintain and expand existing applications as needed. The ability to automate the engineering process allows users, particularly system integrators and original equipment manufacturers (OEM), to set up complex projects much more efficiently and accurately.

- **Improved data management:** A high-quality SCADA system makes it easier to collect, manage, access and analyze your operational data. It can enable automatic data recording and provide a central location for data storage. Additionally, it can transfer data to other systems such as MES and ERP as needed. zenon has a variety of drivers and open interfaces to enable this, even across heterogeneous hardware landscapes.
- **Greater visibility:** One of the main advantages of using SCADA software is the improvement in visibility into your operations. It provides you with real-time information about your operations and enables you to conveniently view that information via an HMI. SCADA software can also help in generating reports and analyzing data.
- **Enhanced efficiency:** A SCADA system allows you to streamline processes through automated actions and user-friendly tools. The data that SCADA provides allows you to uncover opportunities for improving the efficiency of the operations, which can be used to make long-term changes to processes or even respond to real-time changes in conditions.
- **Increased usability:** SCADA systems enable workers to control equipment more quickly, easily and safely through an HMI. Rather than having to control each piece of machinery manually, workers can manage them remotely and often control many pieces of equipment from a single location. Managers, even those who are not currently on the floor, also gain this capability.
- **Reduced downtime:** A SCADA system can detect faults at an early stage and push instant alerts to the responsible personnel. Powered by predictive analytics, a SCADA system can also inform you of a potential issue of the machinery before it fails and causes larger problems. These features can help improve the overall equipment effectiveness (OEE) and reduce the amount of time and cost on troubleshooting and maintenance.
- **Easy integration:** Connectivity to existing machine environments is key to removing data silos and maximizing productivity. zenon features more than 300 available communication protocols to enable simple integration into your existing machinery and network infrastructure. It also features pre-configured drivers, functions and variables that you can use across projects.

- **Unified platform:** This isn't the case with all SCADA systems, but with zenon, you can control all of your equipment and processes using one unified platform, which significantly reduces operational complexity and makes your life easier. All of your data is also available in one platform, which helps you to get a clear overview of your operations and take full advantage of your data. All users also get real-time updates locally or remotely, ensuring everyone on your team is on the same page.

Protective relays are used extensively across the power system to remove any element from service that suffers a short circuit, starts to operate abnormally or poses a risk to the operation of the system. The relaying equipment is aided in this task by **instrument transformers** that sense power conditions and **circuit breakers** that are capable of disconnecting the faulty element when called upon by the relaying equipment.

Due to their critical role in the power system, protective relays should be **acceptance tested** prior to being placed in service and periodically thereafter to ensure reliable performance. In a normal industrial application, **periodic testing** should be done at least every 2 years in accordance with NFPA 70B 2016.

Protective relay testing may be divided into three categories: **acceptance testing**, **commissioning**, and **maintenance testing**. Which of the procedures described below are added to your test plan will depend on the specific project or industry specifications, to be determined by the equipment owner or system engineer.

1. Visual and Mechanical Inspection

Testing and maintenance of protective relays always begins with a thorough visual and mechanical inspection. If the circuit to be tested is in service, **one relay** at a time should be removed (if applicable) so as not to totally disable the protection.

What to check varies depending on the **type of relay**, whether electromechanical, solid-state, or microprocessor-based. Procedures for each type of relay are summarized below:

Inspections and Checks for Electromechanical and Solid State Relays

Electromechanical relays consist of **physical moving parts** to connect a contact within the output component of the relay. The movement of the contact is generated using **electromagnetic forces** from a low-power input signal.

Solid-state relays use power **semiconductor** devices such as **thyristors** and **transistors**, to switch currents up to around a hundred amperes. Solid-state relays have **fast switching speeds** compared with electromechanical relays, and have **no physical contacts** to wear out.

Record and compare the **relay nameplate data** with the applicable project drawings and specifications to ensure the correct equipment with the appropriate options are installed.

Inspect the relay and case for **physical damage** and verify that the entire **unit is clean**. For new installations, be sure that all shipping restraint material has been removed.

Tighten the relay case **connections** and inspect the cover for correct **gasket seal**. Inspect shorting hardware, connection paddles, and/or knife switches.

Inspect the relay unit for **foreign material**, particularly in disk slots of the damping and electromagnets. Remove any foreign material from the case and ensure the cover glass is clean.

Verify **target reset** functionality, disk clearance, contact clearance and spring bias.

Inspect **spiral spring** convolutions. The relay spiral spring should be concentric and should not show signs of overheating. The **disk and contacts** should be inspected for freedom of movement and correct travel.

Bearings and pivots should be clean and demonstrate **fluid movement**. Verify the tightness of all relay mounting hardware and connections. Delicately clean the fine silver contacts using a flexible **burnishing tool** that resembles a superfine file.

Ref : https://www.wikihow.com/Test-a-Relay