Control Systems

Controllers: process controllers, control modes, PID and digital controllers, velocity, adaptive, digital logic, microprocessor control.

Control System & theory

- A **control system** is a system of devices that manages, commands, directs or regulates the behavior of other devices to achieve a desired result.
- The definition of a control system can be simplified as a system which controls other systems to achieve a desired state.
- **Control theory** deals with the control of dynamical systems in engineered processes and machines.
- The objective is to develop a model or algorithm governing the application of system inputs to drive the system to a desired state, while minimizing any *delay*, *overshoot*, or *steady-state error* and ensuring a level of control stability; often with the aim to achieve a degree of optimality.
- To do this, a **controller** with the requisite corrective behavior is required.

- This controller monitors the controlled process variable (PV), and compares it with the reference or set point (SP).
- The difference between actual and desired value of the process variable, called the *error* signal, or SP-PV error, is applied as feedback to generate a control action to bring the controlled process variable to the same value as the set point.
- This is the basis for the advanced type of automation that revolutionized manufacturing, aircraft, communications and other industries.
- This is *feedback control*, which involves taking measurements using a sensor and making calculated adjustments to keep the measured variable within a set range by means of a "final control element", such as a control valve.

- Control theory dates from the 19th century, when the theoretical basis for the operation of governors was first described by James Clerk Maxwell.
- Control theory was further advanced by Edward Routh in 1874, Charles Sturm and in 1895, Adolf Hurwitz, who all contributed to the establishment of control stability criteria; and from 1922 onwards, the development of PID control theory by Nicolas Minorsky.
- A major application of mathematical control theory is in control system engineering, which deals with the design of process control systems for industry.
- Feedback control theory also has applications in life sciences, computer engineering, sociology and operations research.

Types of control loops

- Fundamentally, there are two types of control loops: open loop control and closed loop (feedback) control.

Open Loop Control

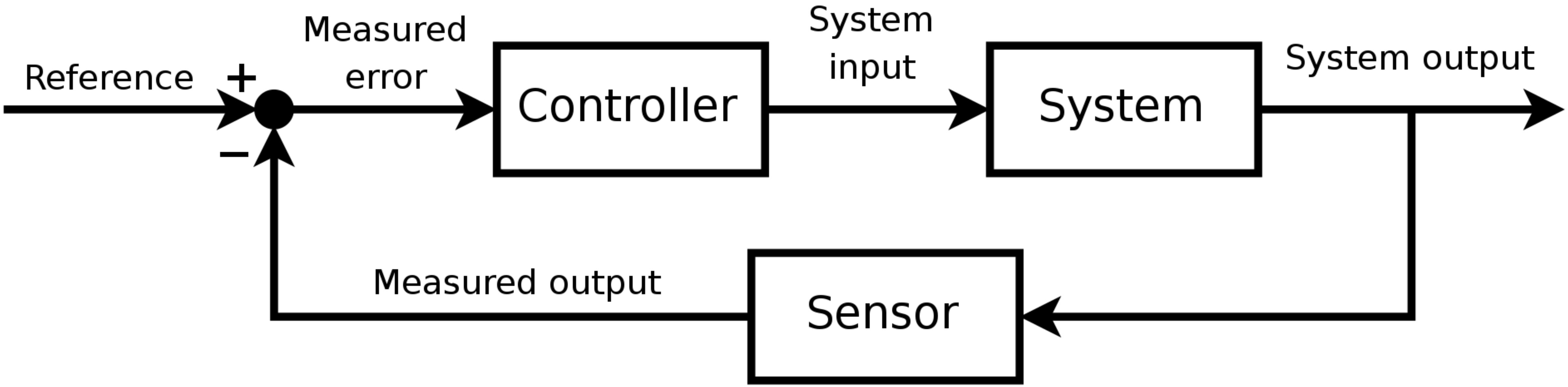
- In open loop control, the control action from the controller is independent of the "process output".
- A good example of this is a central heating boiler controlled only by a timer, so that heat is applied for a constant time, regardless of the temperature of the building.
- The control action is the timed switching on/off of the boiler and the process variable is the building temperature.

Closed Loop Control

- In closed loop control, the control action from the controller is dependent on feedback from the process in the form of the value of the process variable (PV).
- For this reason, closed loop controllers are also called feedback controllers.
- In the case of the boiler analogy, a closed loop would include a thermostat to compare the building temperature (PV) with the temperature set on the thermostat (the set point - SP).
- This generates a controller output to maintain the building at the desired temperature by switching the boiler on and off.

Closed Loop Control

A block diagram of a negative feedback control system using a feedback loop to control the process variable by comparing it with a desired value, and applying the difference as an error signal to generate a control output to reduce or eliminate the error.



Example of a control system

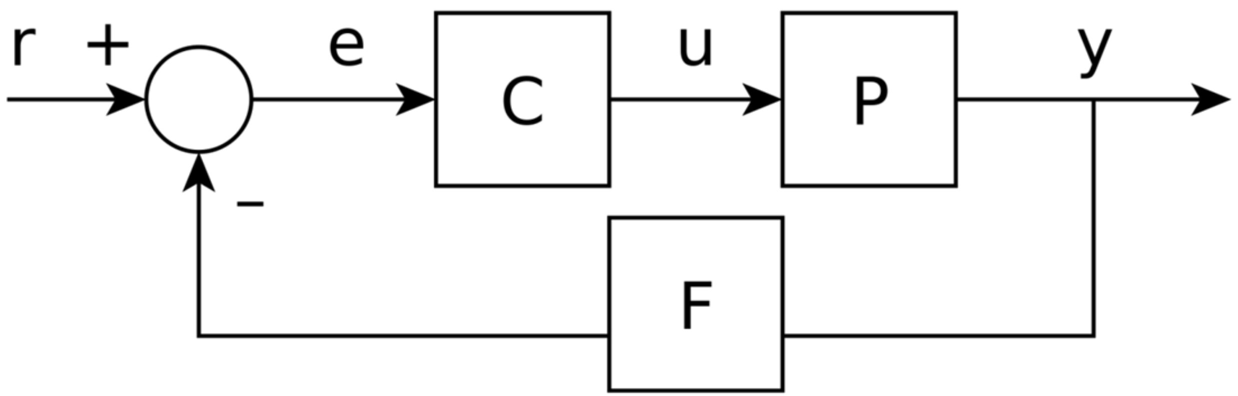
- An example of a control system is a car's cruise control, which is a device designed to maintain vehicle speed at a constant *desired* or *reference* speed provided by the driver.
- The system output is the car's speed, and the control itself is the engine's throttle position which determines how much power the engine delivers.
- A primitive way to implement cruise control is simply to lock the throttle position.
- However, if the cruise control is engaged on a stretch of non-flat road, then the car will travel slower going uphill and faster when going downhill.
- This is an *open-loop controller* because there is no feedback; no measurement of system output (car's speed) is used to alter the control (throttle position).
- As a result, the controller cannot compensate for changes acting on the car, like a change in the slope of the road.

- In a *closed-loop control system*, data from a sensor monitoring the car's speed enters a controller which continuously compares the quantity representing the speed with the reference quantity.
- The difference, called the error, determines the throttle position (the control).
- The result is to match the car's speed to the reference speed.
- Now, when the car goes uphill, the difference between the input (the sensed speed) and the reference continuously determines the throttle position.
- As the sensed speed drops below the reference, the difference increases, the throttle opens, and engine power increases, speeding up the vehicle.
- In this way, the controller dynamically counteracts changes to the car's speed.

Closed-loop transfer function

- In engineering, a **transfer function** (also known as system function or network function) of a system, sub-system, or component is a mathematical function that theoretically models the system's output for each possible input.
- They are widely used in electronics and control systems.
- Consider the closed loop system shown in figure.
- If we assume the controller C, the plant P, and the sensor F are linear and time-invariant (i.e., elements of their transfer function C(s), P(s), and F(s) do not depend on time), the systems can be analyzed using the Laplace transform on the variables.

This gives the following relations:



$$Y(s) = P(s)U(s)$$

$$U(s) = C(s)E(s)$$

$$E(s) = R(s) - F(s)Y(s).$$

Solving for *Y*(*s*) in terms of *R*(*s*) gives

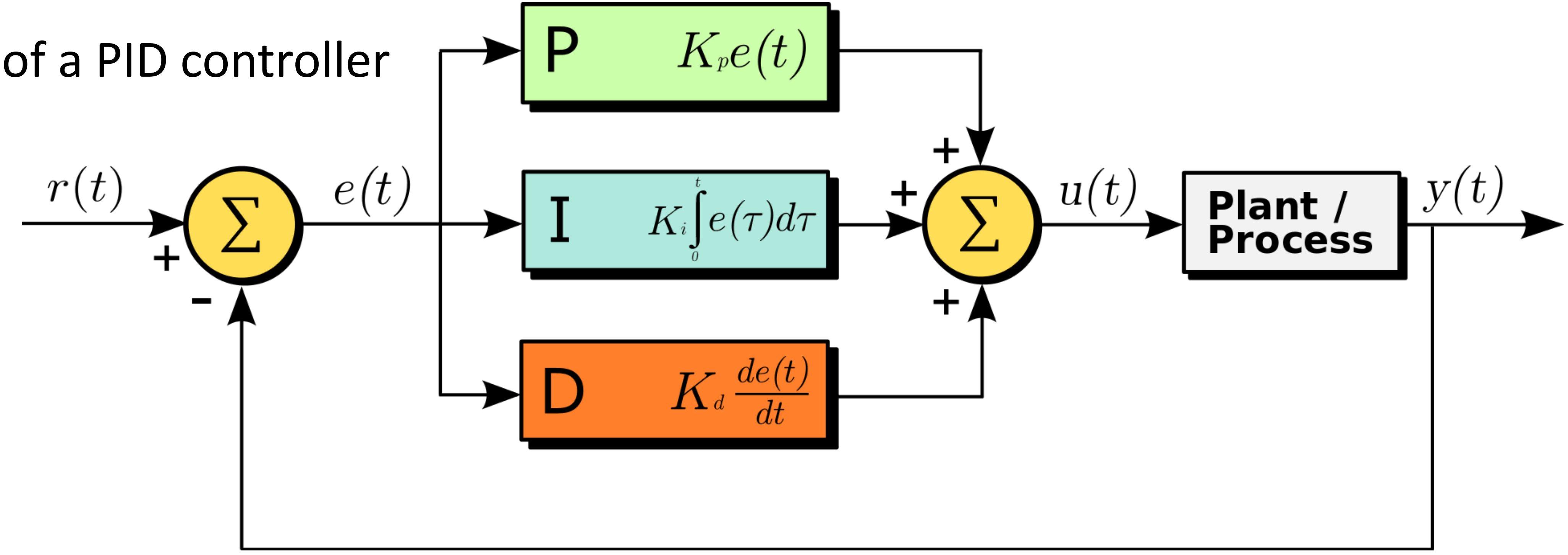
$$Y(s) = \left(\frac{P(s)C(s)}{1 + P(s)C(s)F(s)}\right) R(s) = H(s)R(s).$$

the closed-loop transfer function of the system: $H(s) = \dfrac{P(s)C(s)}{1 + F(s)P(s)C(s)}$

PID Controller

- A proportional–integral–derivative (PID) controller is a control loop feedback mechanism control technique widely used in control systems.
- A PID controller continuously calculates an error value e(t) as the difference between a desired set point and a measured process variable and applies a correction based on proportional, integral, and derivative terms.
- PID is an initials for Proportional-Integral-Derivative, referring to the three terms operating on the error signal to produce a control signal.
- Originally in mechanical controllers, and then using discrete electronics and later in industrial process computers.
- The PID controller is probably the most-used feedback control design.

A block diagram of a PID controller



If u(t) is the control signal, y(t) is the measured output and r(t) is the desired output, and e(t) = r(t) − y(t) is the tracking error, a PID controller has the general form,

$$u(t) = K_P e(t) + K_I \int^t e(\tau)\mathrm{d}\tau + K_D \frac{\mathrm{d}e(t)}{\mathrm{d}t}.$$

r(t) is the desired process value or "set point", and y(t) is the measured process value.

- The desired closed loop dynamics is obtained by adjusting the three parameters K_P, K_I and K_D, often iteratively by "tuning" and without specific knowledge of a plant model.
- Stability can often be ensured using only the proportional term.
- The integral term permits the rejection of a step disturbance.
- The derivative term is used to provide damping or shaping of the response.
- PID controllers are the most well-established class of control systems.
- However, they cannot be used in several more complicated cases, especially if MIMO systems are considered.

Applying Laplace transformation results in the transformed PID controller equation

$$u(s) = K_P\, e(s) + K_I\, \frac{1}{s}\, e(s) + K_D\, s\, e(s)$$

$$u(s) = \left(K_P + K_I\, \frac{1}{s} + K_D\, s\right) e(s)$$

with the PID controller transfer function

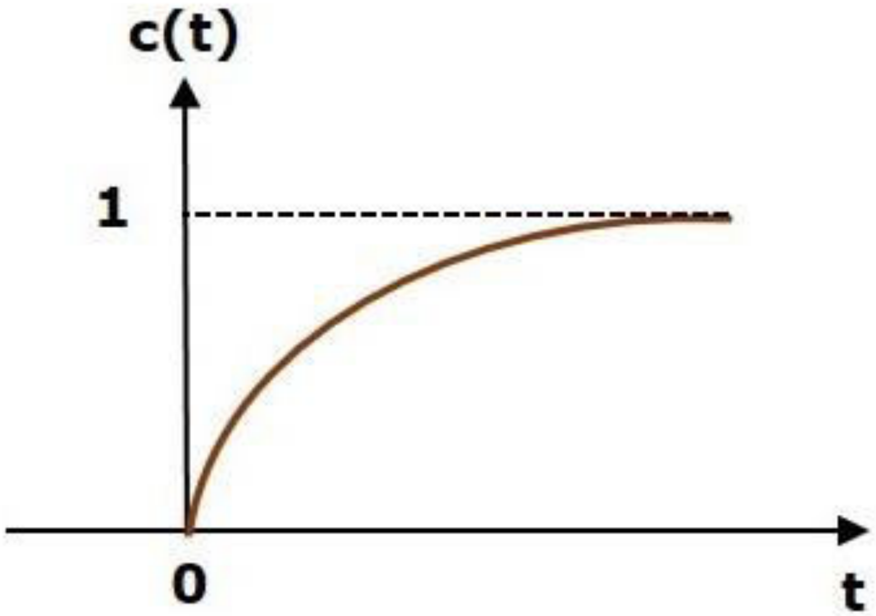
$$C(s) = \left(K_P + K_I\, \frac{1}{s} + K_D\, s\right).$$

Topics in control theory

These are main issues in the analysis of a system before deciding the best control strategy to be applied.

- **Stability**
- A system is said to be stable, if its output is under control. Otherwise, it is unstable.
- A stable system produces a bounded output for a given bounded input.
- This figure shows the response of a stable system.
- We can classify the systems based on stability:

  - Absolutely stable system
  - Conditionally stable system
  - Marginally stable system



Topics in control theory

- **Controllability:** In order to be able to do whatever we want with the given dynamic system under control input, the system must be controllable.
- **Observability:** In order to see what is going on inside the system under observation, the system must be observable.
- If a state is not observable, the controller will never be able to determine the behavior of an unobservable state and hence cannot use it to stabilize the system.
- **Robustness:** A control system must always have some robustness property.
- A robust controller is such that its properties do not change much if applied to a different system.

Types of control systems

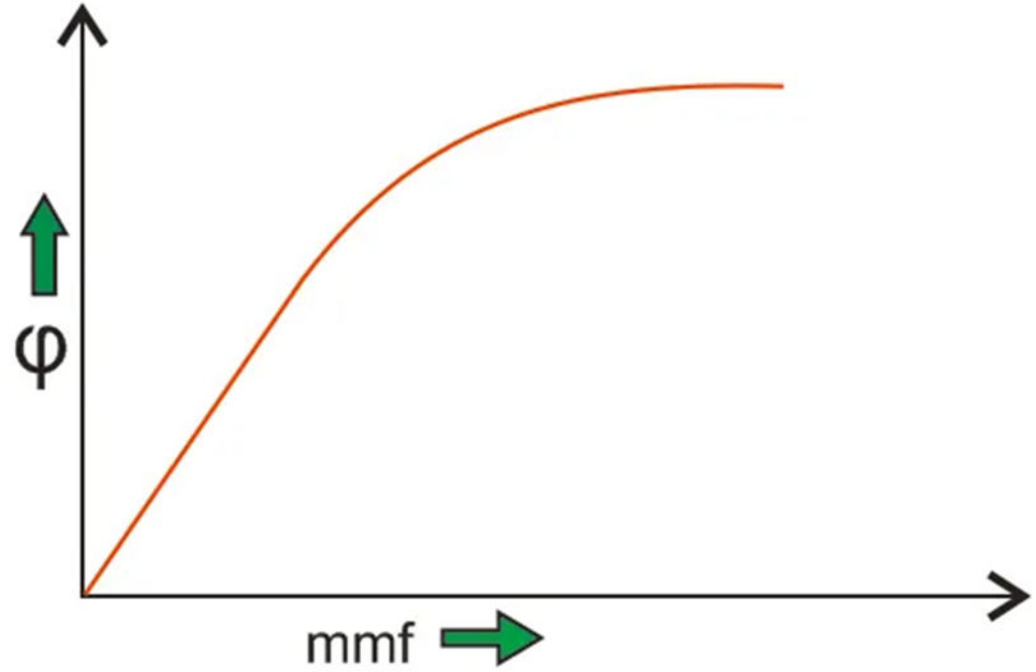
- There are various types of control systems, which can be broadly categorized as linear control systems or non-linear control systems.

Linear Control Systems

- The linear control systems as those types of control systems which follow the principle of superposition.
- A purely resistive network with a constant DC source is an example of Linear Control System.

Non-linear Control Systems

- We can simply define a nonlinear control system as a control system which does not follow the principle of Superposition.
- In real life, all control systems are non-linear, linear control systems only exist in theory.
- A well-known example of a non-linear system is a magnetization curve or no load curve of a DC machine.
- No load curve gives us the relationship between the air gap flux and the field winding mmf.



Analog or Continuous System

- In this control system, we have a continuous signal as the input to the system.
- We may have various sources of continuous input signal like sinusoidal type signal input source, square type of signal input source etc.

Digital or Discrete System

- In these types of control systems, we have a discrete signal (or signal may be in the form of pulse) as the input to the system.
- These signals have a discrete interval of time.
- Now there are various advantages of discrete or digital system over the analog system.

Single Input Single Output Systems

- These are also known as SISO systems.
- In this, the system has single input for a single output.
- Example : An audio system, in which the control input is the input audio signal and the output is the sound waves from the speaker.

Multiple Input Multiple Output Systems

- These are also known as MIMO systems.
- In this, the system has multiple outputs for multiple inputs.
- For example, modern large telescopes have mirrors composed of many separate segments each controlled by an actuator.

Lumped Parameter System

- The control systems, in which the various active and passive components are assumed to be concentrated at a point these are called lumped parameter type of system.
- Analysis of such type of system is very easy which includes differential equations.

Distributed Parameter System

- The control systems, in which the various active (like inductors and capacitors) and passive parameters (resistor) are assumed to be distributed uniformly along the length and that’s why these are called distributed parameter type of system.
- Analysis of such type of system includes partial differential equations.

Decentralized systems control

- In Decentralized control the system is controlled by multiple controllers.
- Decentralization helps control systems to operate over a larger geographical area.

Deterministic and stochastic systems control

- A deterministic system is a system in which no randomness is involved in the development of future states of the system.
- Deterministic control systems are designed for external deterministic disturbances or deterministic initial values.
- A stochastic system has a random probability distribution or pattern that may be analyzed statistically but may not be predicted precisely.
- In stochastic optimal control, a controller attempts to achieve a desired behavior in spite of noise.

List of the main control techniques

Adaptive control

- It uses on-line identification of the process parameters, or modification of controller gains, thereby obtaining strong robustness properties.
- Adaptive controls were applied for the first time in the aerospace industry in the 1950s, and have found particular success in that field.

Hierarchical control system

- It is a type of control system in which a set of devices and governing software is arranged in a hierarchical tree.

Optimal control

- It is a particular control technique in which the control signal optimizes a certain "cost index“.
- For example, in the case of a satellite, the jet thrusts needed to bring it to desired trajectory that consume the least amount of fuel.

Robust control

- It deals explicitly with uncertainty in its approach to controller design.
- Examples of modern robust control techniques include safe protocols designed for control of electric loads in Smart Power Grid applications.

Intelligent control

- It uses various AI computing approaches like artificial neural networks, fuzzy logic, machine learning, evolutionary computation and genetic algorithms or a combination of these methods, such as neuro-fuzzy algorithms, to control a dynamic system.

Stochastic control

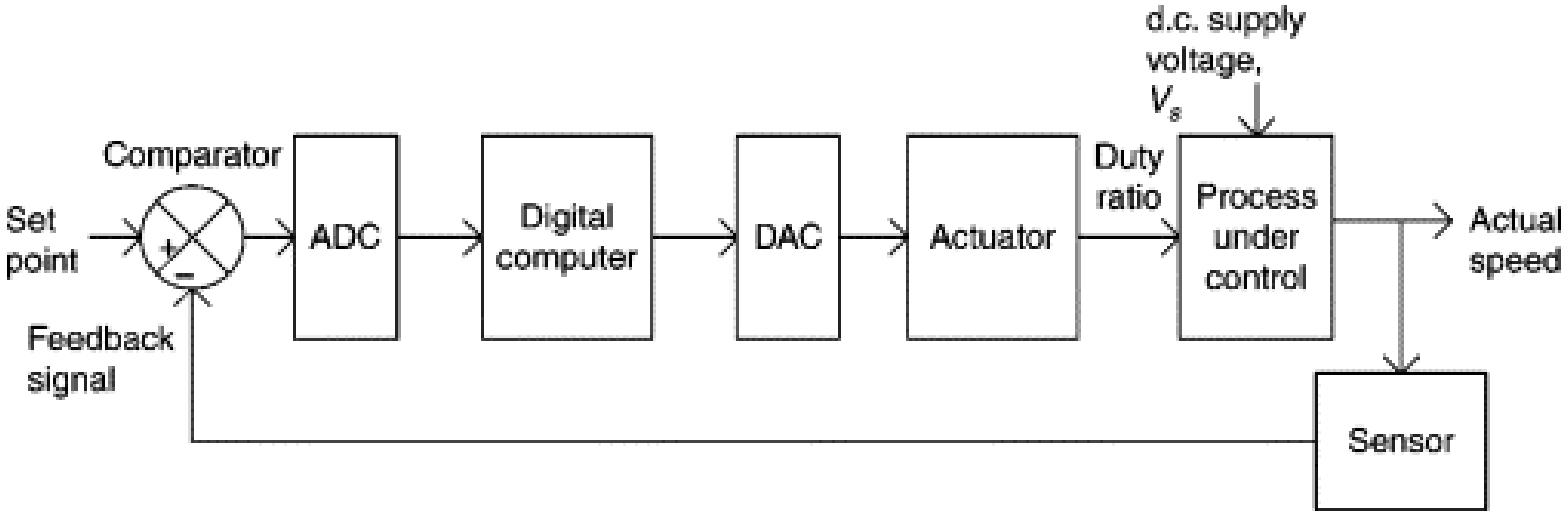
- It deals with control design with uncertainty in the model.
- In typical stochastic control problems, it is assumed that there exist random noise and disturbances in the model and the controller, and the control design must take into account these random deviations.

Digital Controller

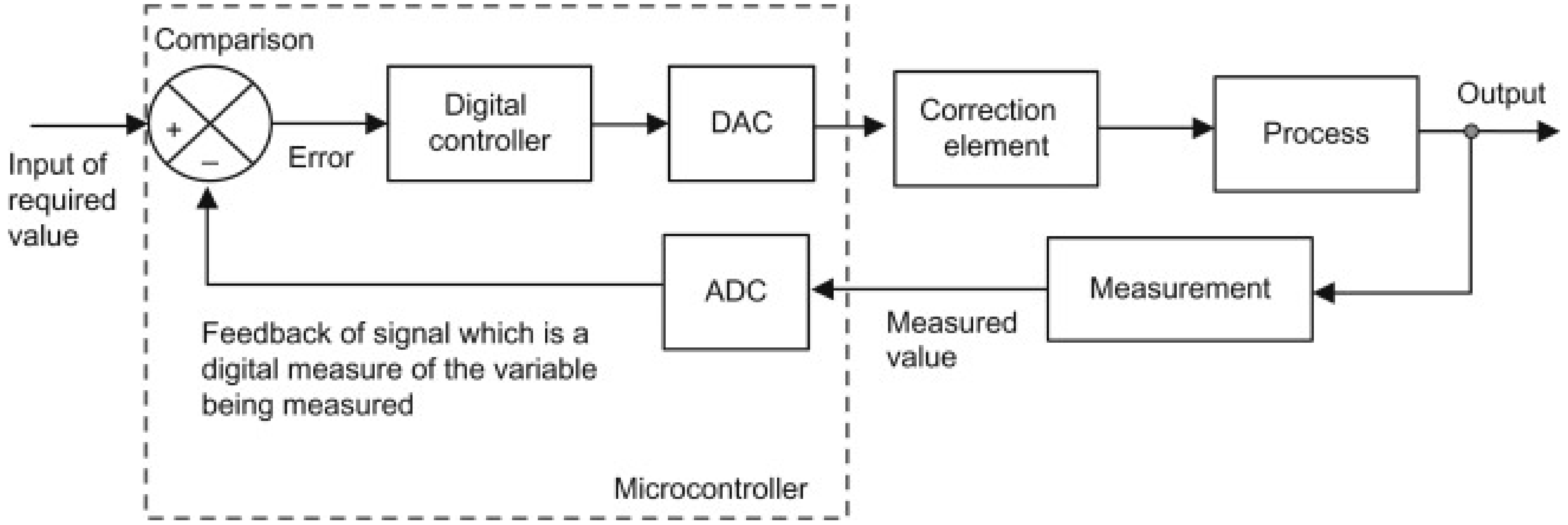
- **Digital control** is a branch of control theory that uses digital computers to act as system controllers.
- A digital control system processes signals coming from sensors by means of computer.
- A digital controller is a system used for controlling closed-loop feedback systems.
- The controller implements algebraic algorithms such as filters and compensatory to regulate, correct, or change the behavior of the controlled system.
- The analogue signal (continuous in value and time) has to be sampled and take discrete values at given time intervals.
- This process is known as signal digitalization.
- **Direct digital control** is the automated control of a condition or process by computer.

Direct digital control

- Direct digital control takes a centralized network-oriented approach.
- All instrumentation is gathered by various analog and digital converters which use the network to transport these signals to the central controller.
- The centralized computer then follows all of its production rules and causes actions to be sent via the same network to valves, actuators, and other heating, ventilating, and air conditioning components that can be adjusted.
- Direct digital control is often used to control heating, ventilating, and air conditioning devices such as valves via microprocessors using software to perform control logic.
- These systems may be mated with a software package that graphically allows operators to monitor, control, alarm and diagnose building equipment remotely.



Block diagram of closed-loop digital control system.

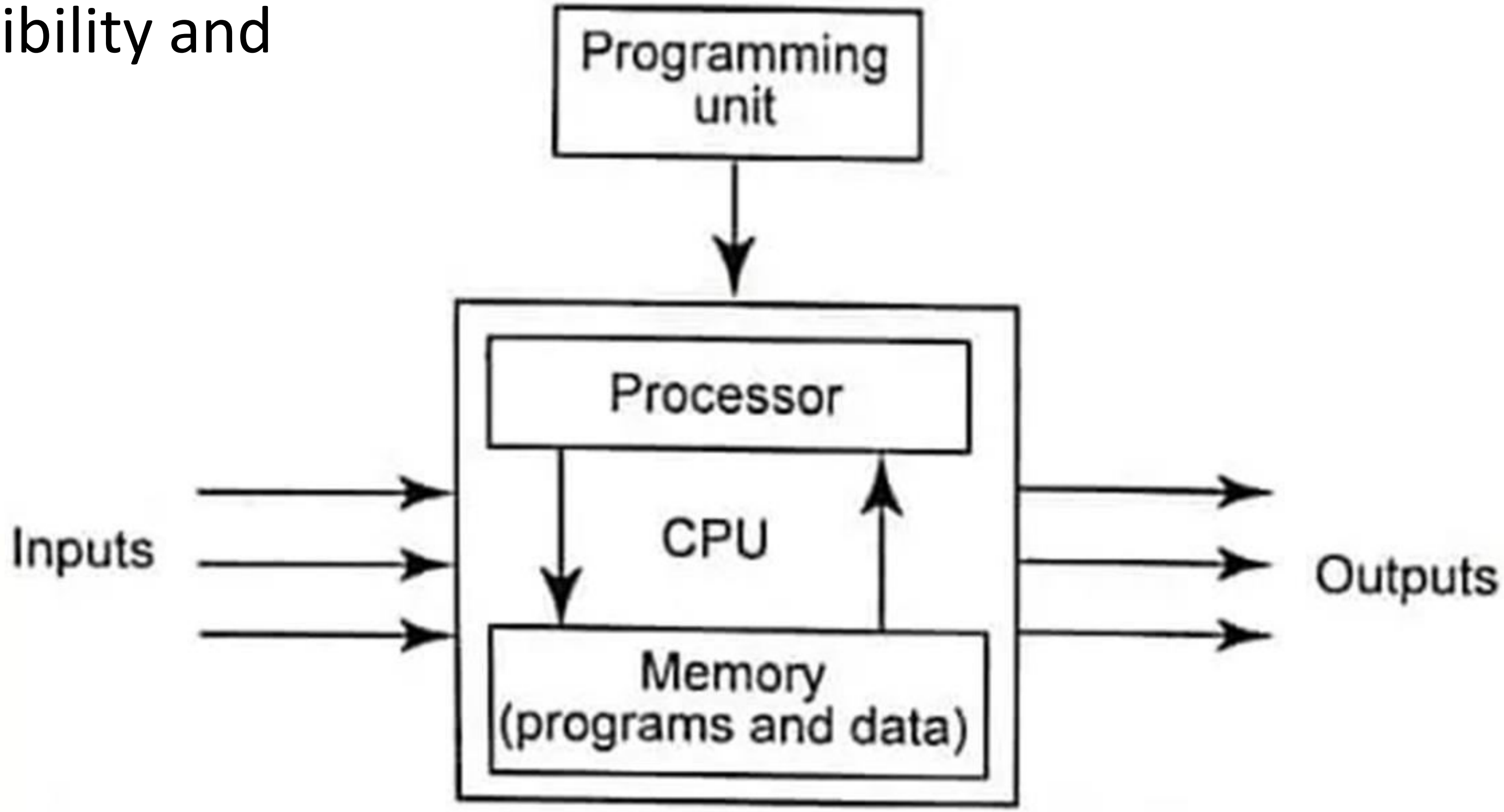


The basic elements of a digital closed-loop control system.

Microcontrollers

- Microprocessors are essential to many of the products we use every day such as TVs, cars, radios, home appliances and of course, computers.
- Microprocessor based controllers are called as microcontrollers.
- Microcontroller is a digital integrated circuit which serves as a heart of many modern control applications.
- Microcontrollers are employed in automation and control applications such as microwave ovens, washing machines, dish washers, engine management systems etc.
- Microcontrollers are embedded inside some other device (often a consumer product) so that they can control the features or actions of the product.
- Therefore, it is also called as embedded controller.

- Because of its relatively low cost, it is a natural choice for design.
- It performs many of the functions traditionally done by simple logic circuitry, sequential control circuits, timers or a small microcomputer.
- Microcontrollers are generally compact in construction, small in size, flexibility and consume less power.



Advantages of Microcontroller:

- They can process data very quickly.
- Due to these fast speeds they can react very quickly to change in the control system.
- Control systems can run through out the year.
- They can work in places where it would be dangerous for a human.
- Outputs are consistent and error free.
- Low level signals from sensors, once converted to digital, can be transmitted long distances virtually error-free.
- A microprocessor can easily handle complex calculations and control strategies
- Long-term memory is available to keep track of parameters in slow-moving systems
- Changing the control strategy is easy by loading in a new program; no hardware changes are required.