Tishk International University – Mechatronics Department

Digital Control Systems
(ME 412)

Lecture (2)

Analog and Digital Control Systems

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Digital and Analog:

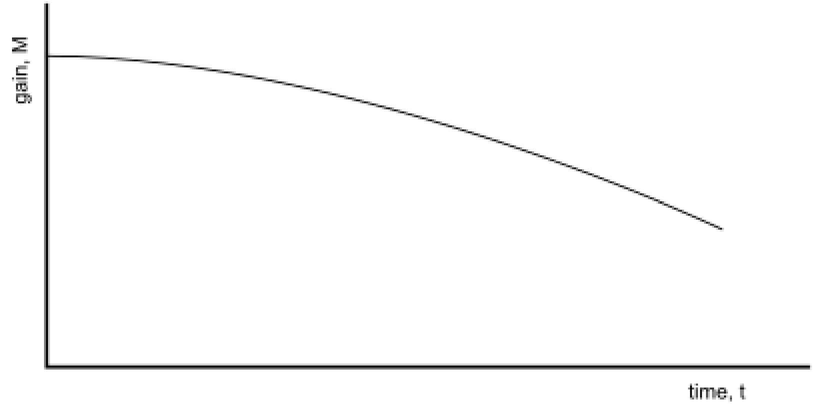
There is a big difference between analog and digital systems, as well as between analog data and digital data.

Continuous time:

A signal is called continuous time if it is defined at every time t.

Analog system:

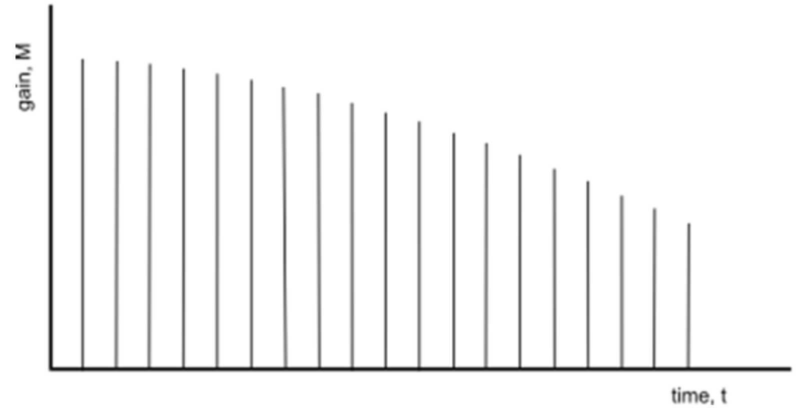
A system is continuous time if it takes a continuous time input signal and produces a continuous time output signal.



Digital and Analog:

Discrete-time:

A signal is called discrete-time if it is only defined for particular points in time.

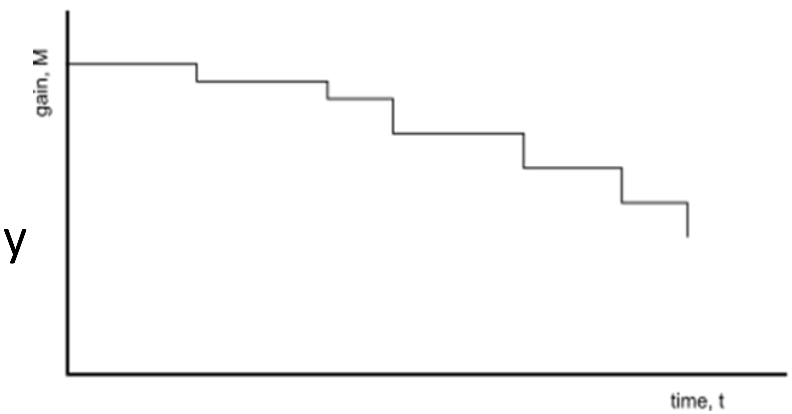


Discrete-time system:

A discrete-time system takes discrete-time input signals and produces discrete-time output signals.

Quantized signal:

A signal is called quantized if it can only take certain values. Notice how the waveform can only take certain values at the sampling period. This image is discrete in size, but continuous in time.



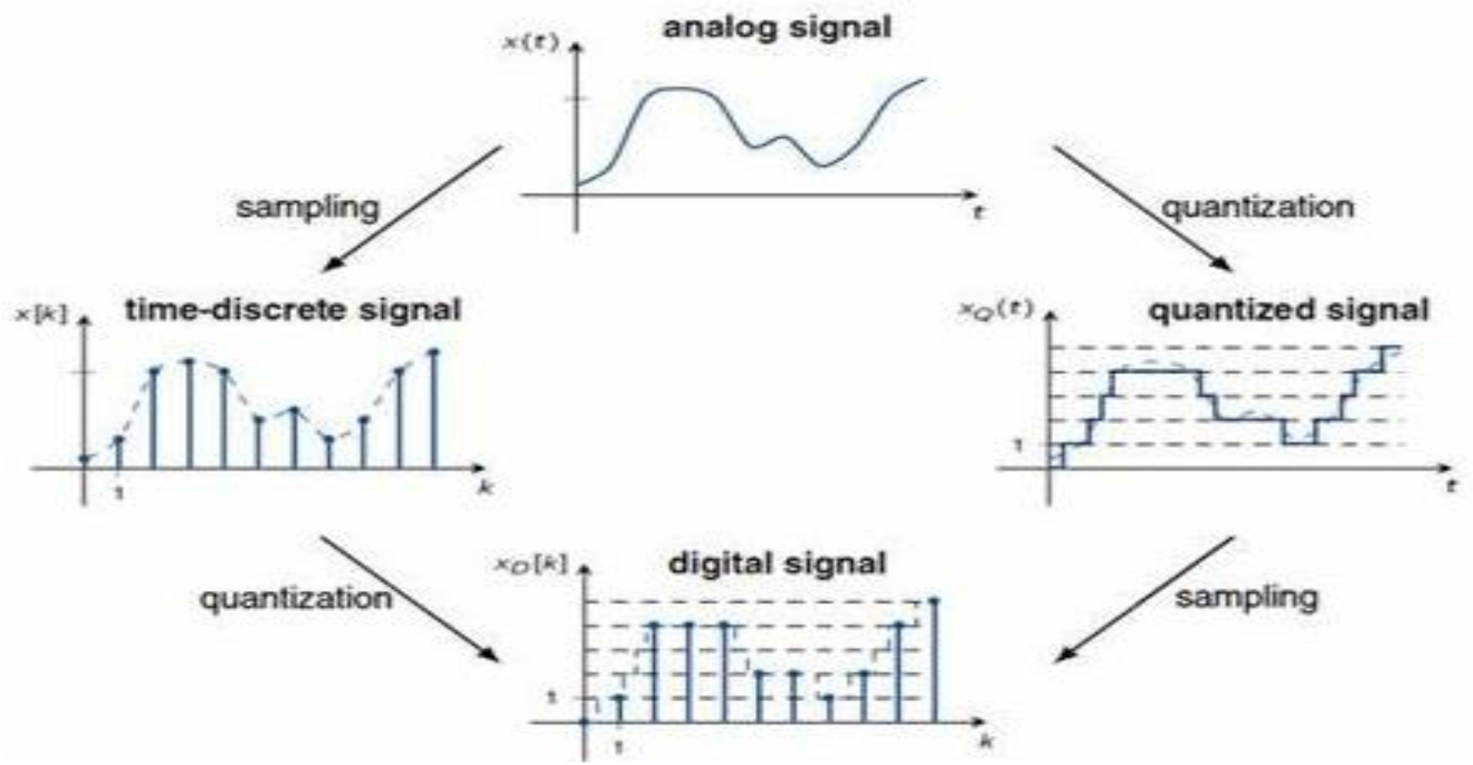
Continuous and Discrete Systems:

Continuous-time Systems:

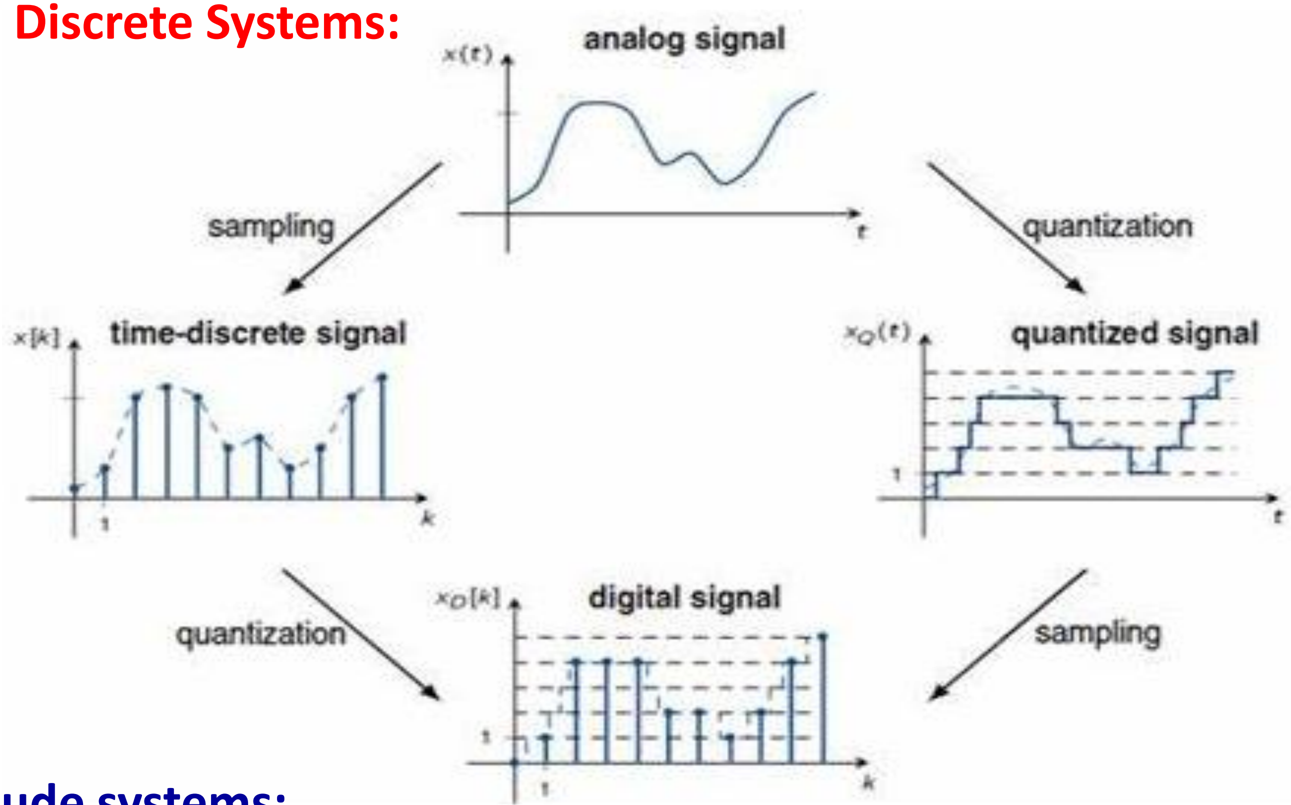
A system is considered **continuous-time** if the signal exists for all time.

Discrete Systems: Discrete systems can be:

- Discrete time (sampled)
- Discrete magnitude (quantized)
- Discrete time and magnitude (digital)



Continuous and Discrete Systems:



Discrete magnitude systems:

Are systems where the signal value can only have certain values.

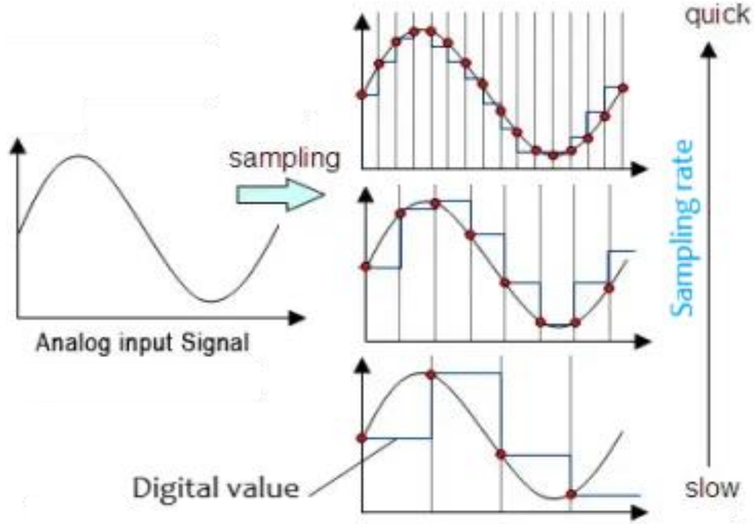
Discrete time systems:

Are systems where signals are only available at particular times.

Computer systems are discrete, in that data is only read at specific discrete time intervals, and the data can have only a limited number of discrete values.

Sampling Time:

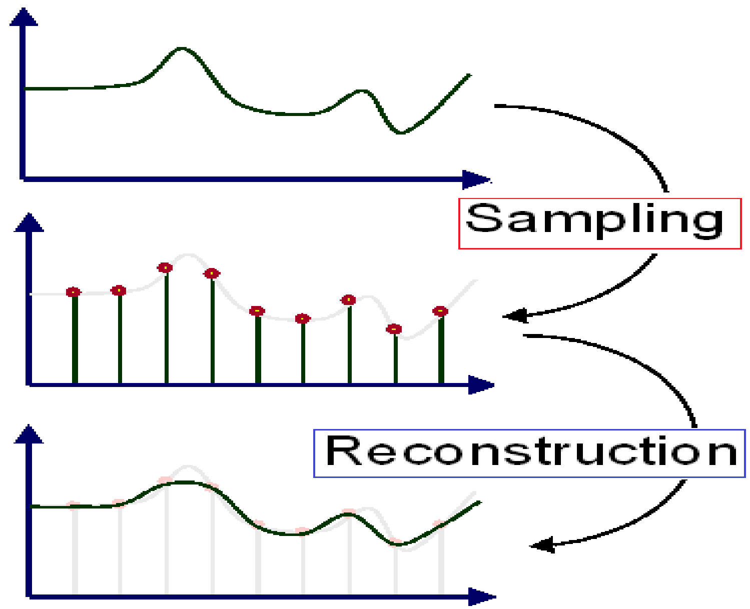
A discrete-time system has a **sampling time**, such that each discrete value occurs at multiples of the given sampling time (T).



Sampling and Reconstruction:

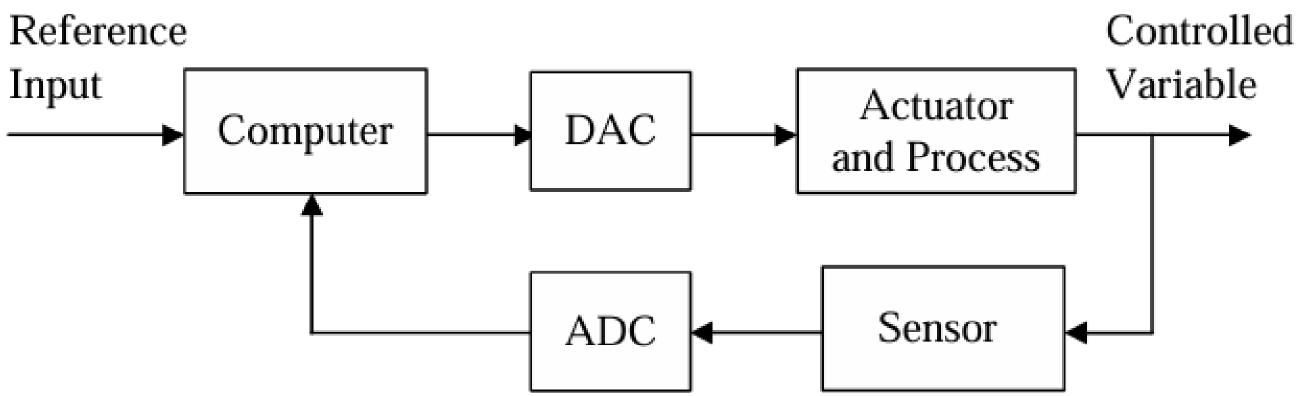
Sampling: process of converting analog information into digital data.

Reconstruction: process of converting digital data into an analog signal.



Digital Control System Structure:

To control a mechatronic system using a digital controller, the controller must receive measurements from the plant and then send control signals to the actuator that effectuate the control action. The plant, sensors, and actuator are analog systems, while the controller is implemented in a computer. Therefore, analog-to-digital converters (ADC) and digital-to-analog converters (DAC) are required.



Why Digital Control?

Digital control of mechatronic systems offers several advantages:

1. **Accuracy and precision:** Digital controllers can process data with high precision, resulting in more precise control of the system.
2. **Complex control algorithms:** Digital systems allow for the implementation of sophisticated control algorithms (such as adaptive controllers, fuzzy logic, or neural networks) that can enhance performance.
3. **Flexibility and reprogramming:** Digital controllers can be easily reprogrammed or updated, allowing for modifications and improvements without hardware changes.
4. **Integration with other systems:** Digital control systems can seamlessly integrate with software for monitoring, diagnostics, and data analysis, enhancing overall system functionality.
5. **Noise immunity:** Digital signals are less susceptible to noise than analog signals, improving the reliability of control processes.

Why Digital Control?

6. **Real-time processing:** Modern digital controllers can handle real-time processing, allowing for immediate responses to changes in the system.
7. **Cost-effectiveness:** Advances in digital technology have contributed to lower costs, making them more accessible.
8. **Communication capabilities:** Digital systems can easily interface with communication protocols, allowing for remote monitoring and control.

These advantages make numerical control a preferred choice in many modern mechatronics applications, from robotics to automotive systems.

Analog and Digital Controllers:

	Analog Controllers	Digital Controllers
Signal Type	Use continuous signals.	Use discrete signals.
Response Time	Provide instantaneous responses due to continuous operation.	May have a slight delay due to the sampling and computational time.
Control Complexity	Limited to simple control strategies.	Capable of implementing complex algorithms.
Flexibility	Changes require hardware modifications	Easily reprogrammable, allowing for updates and modifications through software.
Noise Immunity	It is affected by noise and negatively affects performance.	Less affected by noise, errors can be checked more easily.

Analog and Digital Controllers:

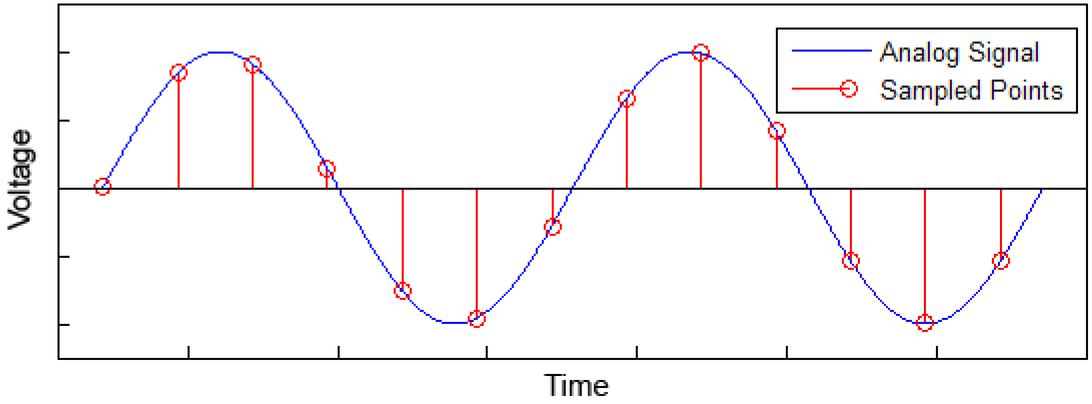
	Analog Controllers	Digital Controllers
Components	Consists of resistors, capacitors, operational amplifiers, and other analog components.	Comprised of microcontrollers, DSPs, and other digital electronics.
Cost and Size	Less expensive for basic applications but expensive for complex systems.	Cost is more effective for complex systems due to integration and functionality.
Maintenance & Calibration	require regular calibration and maintenance to ensure accuracy.	Typically have self-diagnostic features and require less frequent maintenance.
Integration with Other Systems	Integration with digital systems can be challenging and often requires additional conversion equipment.	Easily integrate with other digital systems and networks for monitoring and control.

Sampled-time Signals:

- Most signals of interest are continuous-time signals.
- Computers can process discrete-time signals using flexible and powerful algorithms.

What is Sampling?

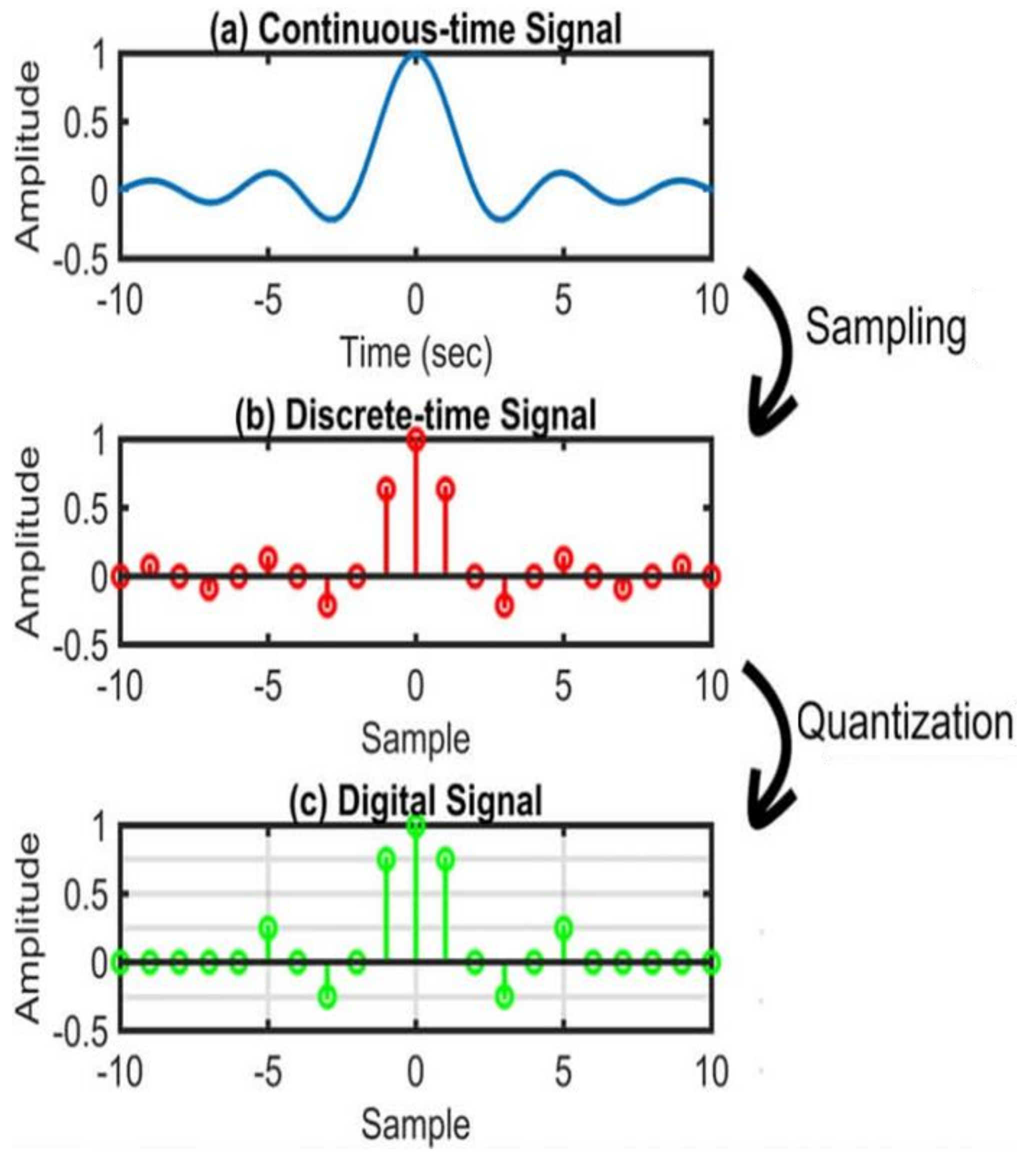
Sampling a continuous time signal produces a discrete time signal by selecting values of the continuous time signal at equally spaced points in time (Ts).
Thus, sampling a continuous-time signal (Y) with a sampling period (Ts) yields a discrete-time signal (Y̌).
The angular sampling frequency is given by $\omega s=2\pi/Ts$.



Basic Concepts in Sampling:

- **Sampling Period (Ts):** This is the fixed time period in which samples are taken from a continuous signal. It determines how frequently data is collected and affects the performance of the system.

- **Quantization:** After sampling, the continuous signal is converted to discrete values after being approximated at a limited number of levels, which can lead to errors known as quantization noise.



Quantization Error:

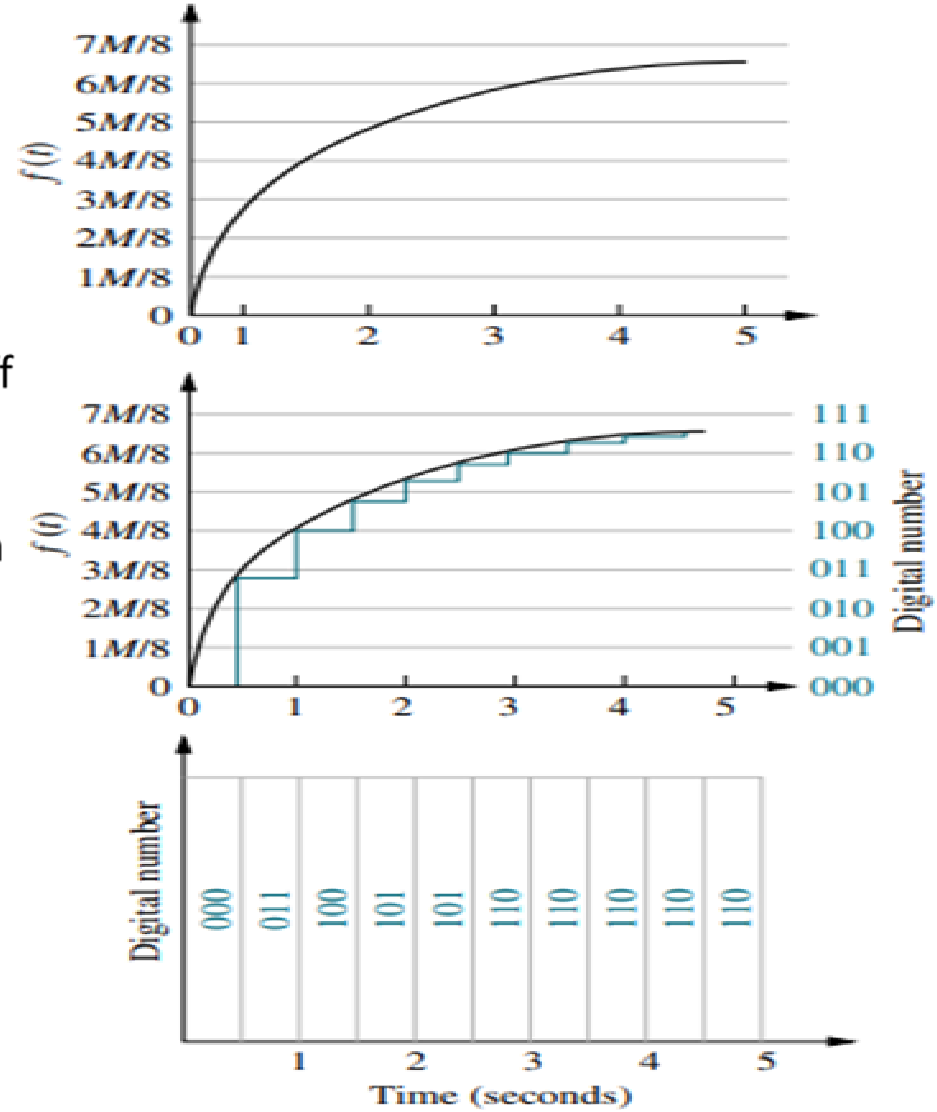
There will be an error for each digitized analog value. This error is called the quantization error.

Example:

For 3-bit ADC with M Volts full-scale voltage, assume that the quantization process rounds off the analog voltage to the next higher or lower level, the maximum value of the quantization error is 1/2 the difference between quantization levels in the range of analog voltages from 0 to (7M/8). In general, for any system using roundoff, the quantization error will be:

$$Q.Error = \left(\frac{1}{2}\right)\left(\frac{M}{2^n}\right) = \left(\frac{M}{2^{n+1}}\right)$$

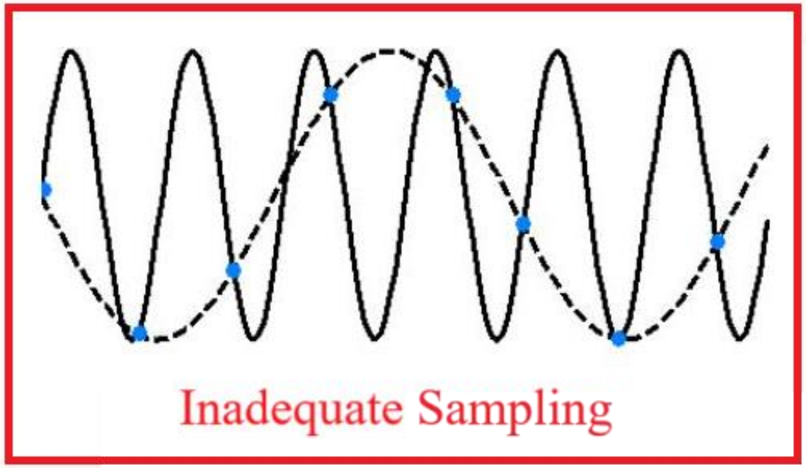
If M= 5 Volts, and n=3 bits, then Q. Error is 0.5556 Volts.

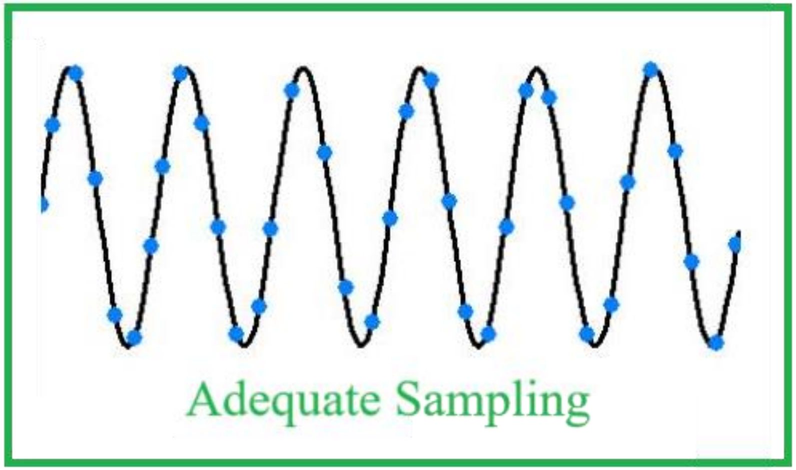


Basic Concepts in Sampling:

- **Nyquist Theorem:** This theorem states that to avoid aliasing (the distortion that occurs when a signal is under-sampled), the sampling frequency must be at least twice the highest frequency present in the signal. This is known as the Nyquist rate.

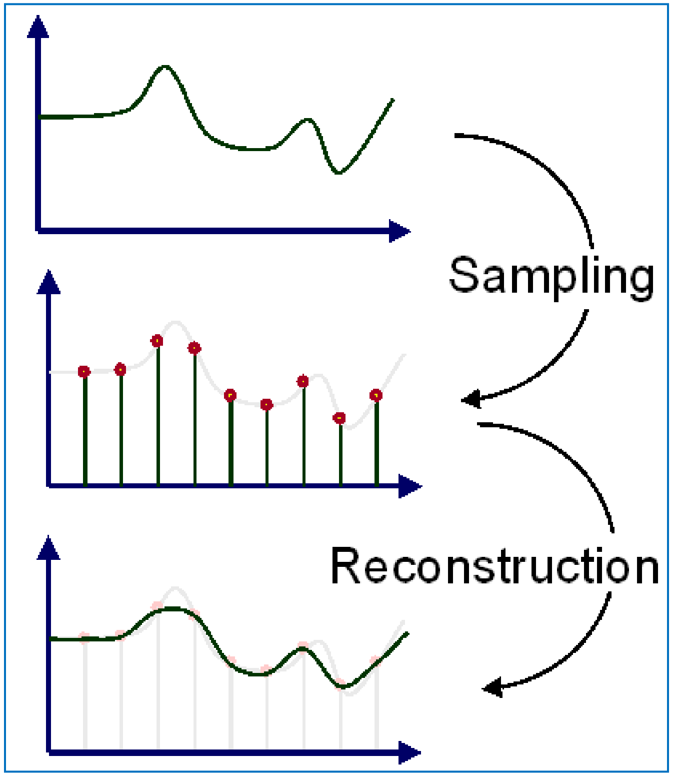
- **Aliasing:** If the sampling frequency is too low, the higher frequency components of the signal can be misrepresented as lower frequencies, leading to inaccurate system behavior.

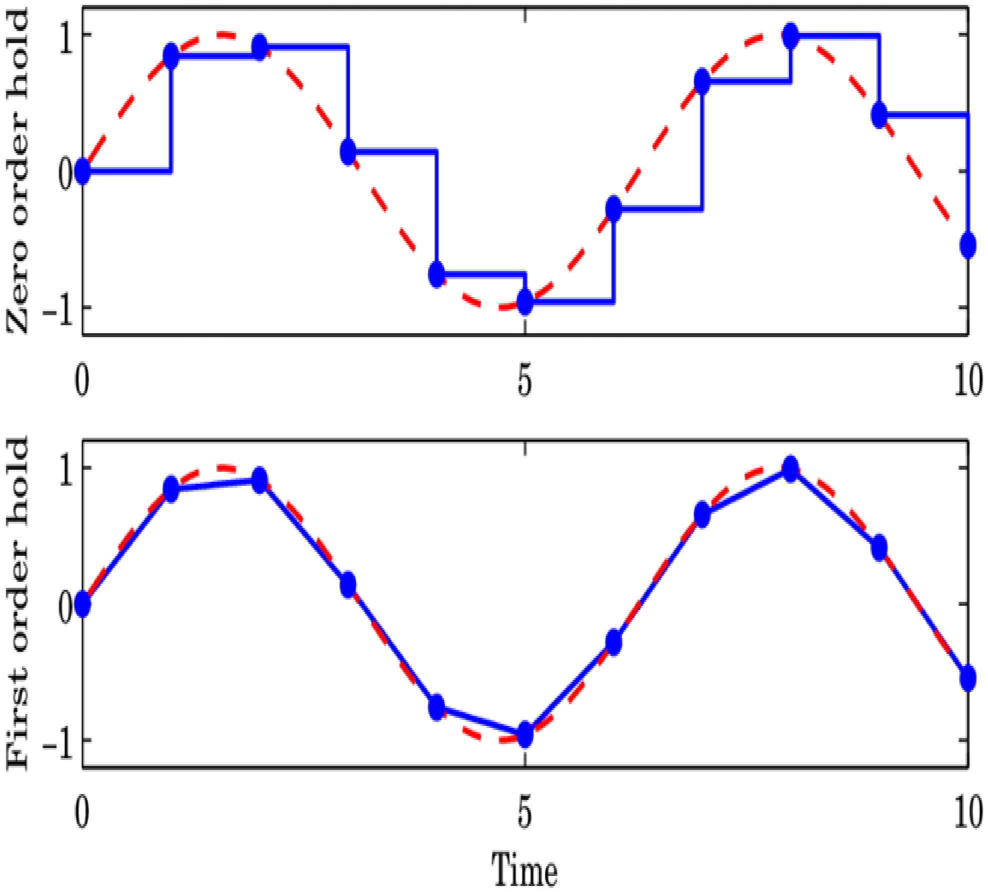




Basic Concepts in Sampling:

- **Z-Transform:** In the analysis of sampled data systems, the z-transform is used to analyze and design digital controllers.
- **Reconstruction:** Once the system has processed the sampled data, the original continuous signal can be reconstructed (using zero-hold unit for example) to maintain continuity in the output.





Choosing the Right Sampling Frequency:

Choosing the right sampling frequency in discrete-time systems is critical when designing mechatronics systems to ensure accurate efficient system performance.

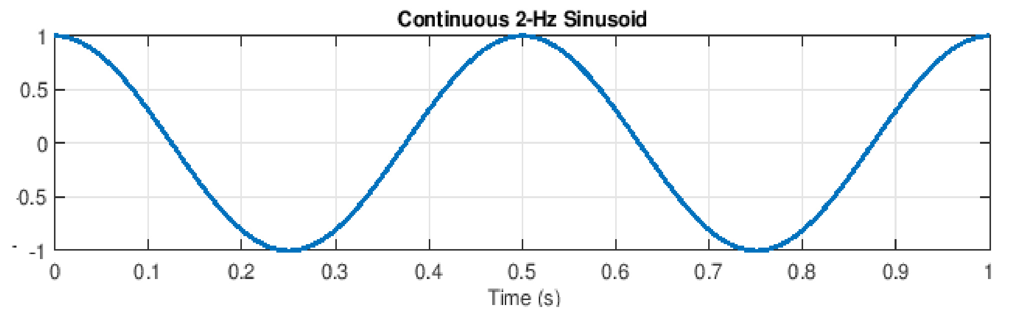
The following are the key considerations and steps for selecting a sampling frequency:

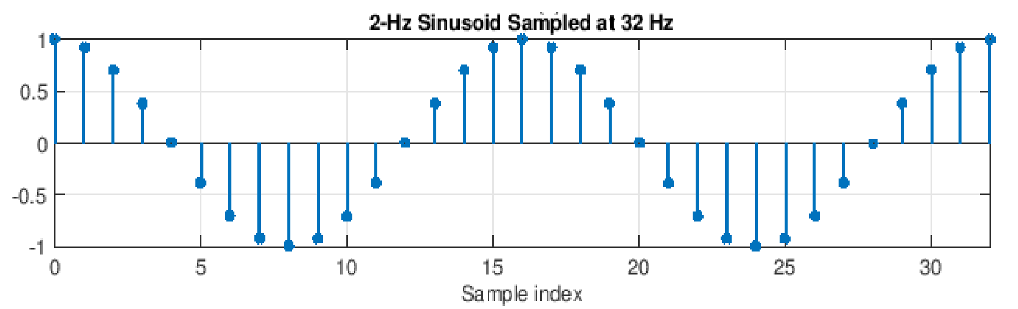
1. Understand the Signal Characteristics:

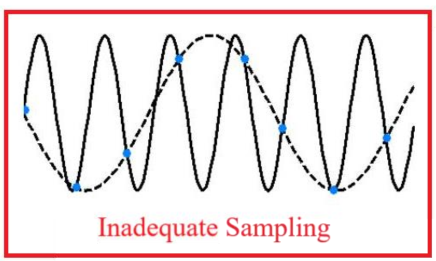
- Bandwidth: Determine the highest frequency component of the signal.
- Nyquist rate: According to the Nyquist theorem, the sampling frequency (fs) should be at least twice the highest frequency component in the signal.

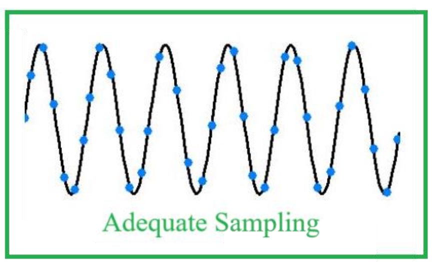
2. Consider Aliasing:

- Risks of aliasing: If the sampling frequency is lower than the Nyquist rate, it leads to distortion. Make sure that your sampling frequency is high enough to mitigate these risks.









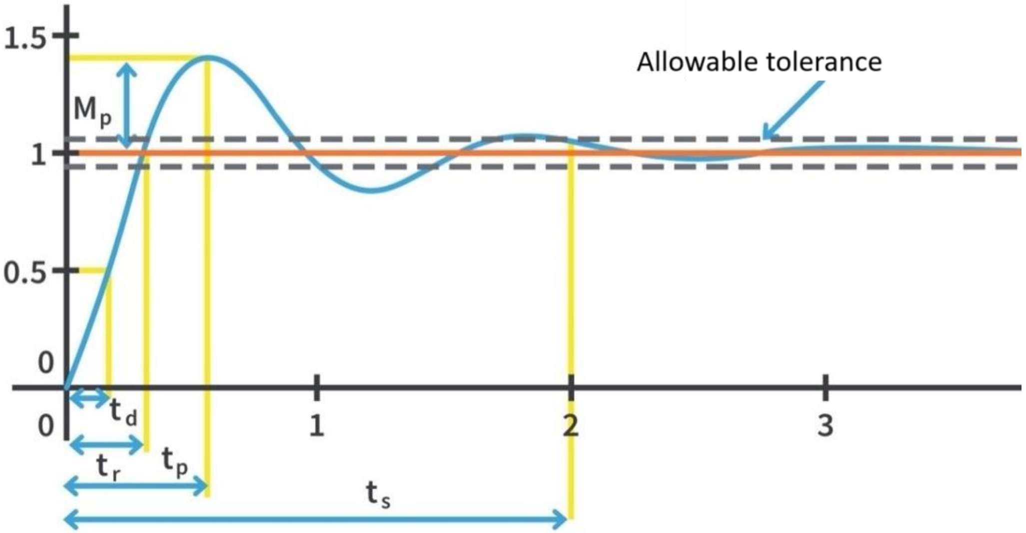
Choosing the Right Sampling Frequency:

3. **Consider Practical Limitations:**

- System limitations: Consider the capabilities of the sensors and the processing power of the digital controller. The sampling frequency should not exceed what the hardware can handle.
- Latency and Delay: Higher sampling rates can introduce processing delays. Balance the need for high accuracy with acceptable system response times.

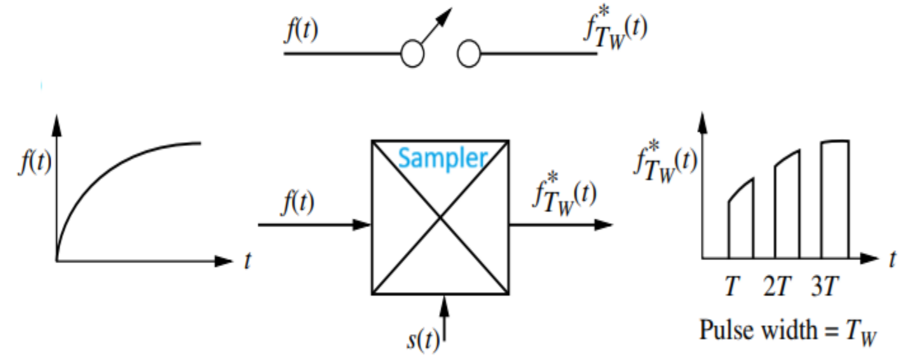
4. **Dynamic System Requirements:**

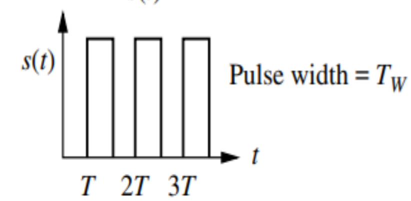
- Response Time: Faster systems may require higher sampling rates to ensure responsive control.
- Stability: Ensure that the sampling frequency supports system stability.



Sampler Model:

If s(t) is a sequence of pulses of width Tw, constant amplitude, and uniform rate, the sampled output will consist of a sequence of sections of f(t) at regular intervals:





$$\boxed{f^*_{T_W}(t) = f(t)s(t) = f(t)\sum_{k=-\infty}^{\infty} u(t-kT) - u(t-kT-Tw)}$$

$$F^*_{T_W}(s) = \sum_{k=-\infty}^{\infty} f(kT)\left[\frac{e^{-kTs}}{s} - \frac{e^{-kTs-T_Ws}}{s}\right] = \sum_{k=-\infty}^{\infty} f(kT)\left[\frac{1-e^{-T_Ws}}{s}\right]e^{-kTs}$$

Replacing e^{-T_WS} with its series expansion,

$$F^*_{T_W}(s) = \sum_{k=-\infty}^{\infty} f(kT)\left[\frac{1-\left\{1-T_Ws+\frac{(T_Ws)^2}{2!}-\ldots\right\}}{s}\right]e^{-kTs}$$

For small T_W,

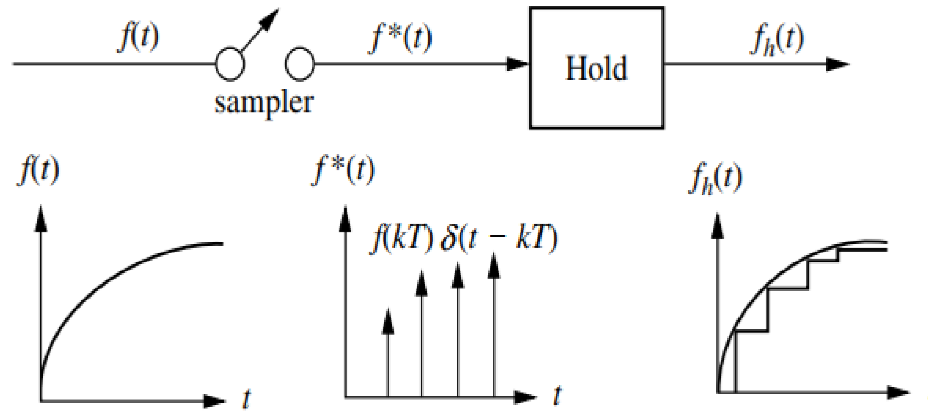
$$F^*_{T_W}(s) = \sum_{k=-\infty}^{\infty} f(kT)\left[\frac{T_Ws}{s}\right]e^{-kTs} = \sum_{k=-\infty}^{\infty} f(kT)T_We^{-kTs}$$

Finally, converting back to the time domain,

$$f^*_{T_W}(t) = T_W\sum_{k=-\infty}^{\infty} f(kT)\delta(t-kT)$$

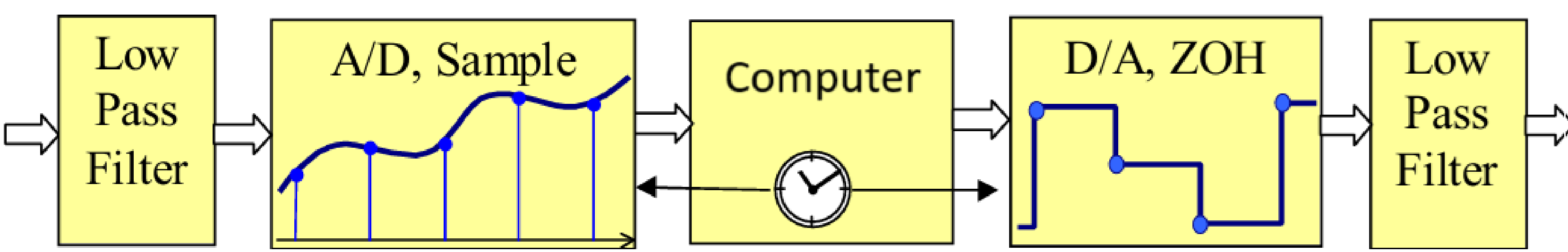
What is Zero-Order Hold?

The zero-order hold (ZOH) is a method used to reconstruct signals in real time. The continuous signal is created from its samples by holding each sample constant for a specified interval until the next sample is received.



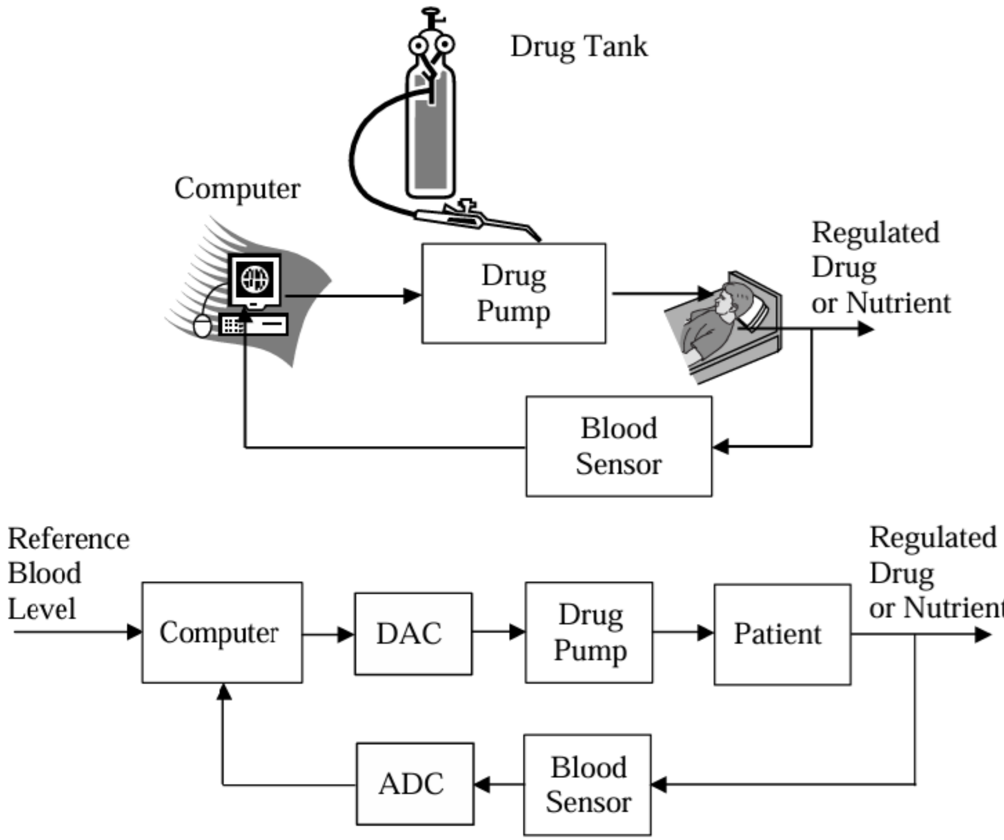
- The zero-order hold generates step approximations of the original signal.
- The transfer function of the zero-order hold is given by;

$$\boxed{G_{ZOH}(s) = \frac{F_{h(s)}}{\overset{*}{F}_{(s)}} = \left(\frac{1 - e^{-Ts}}{s}\right)}$$



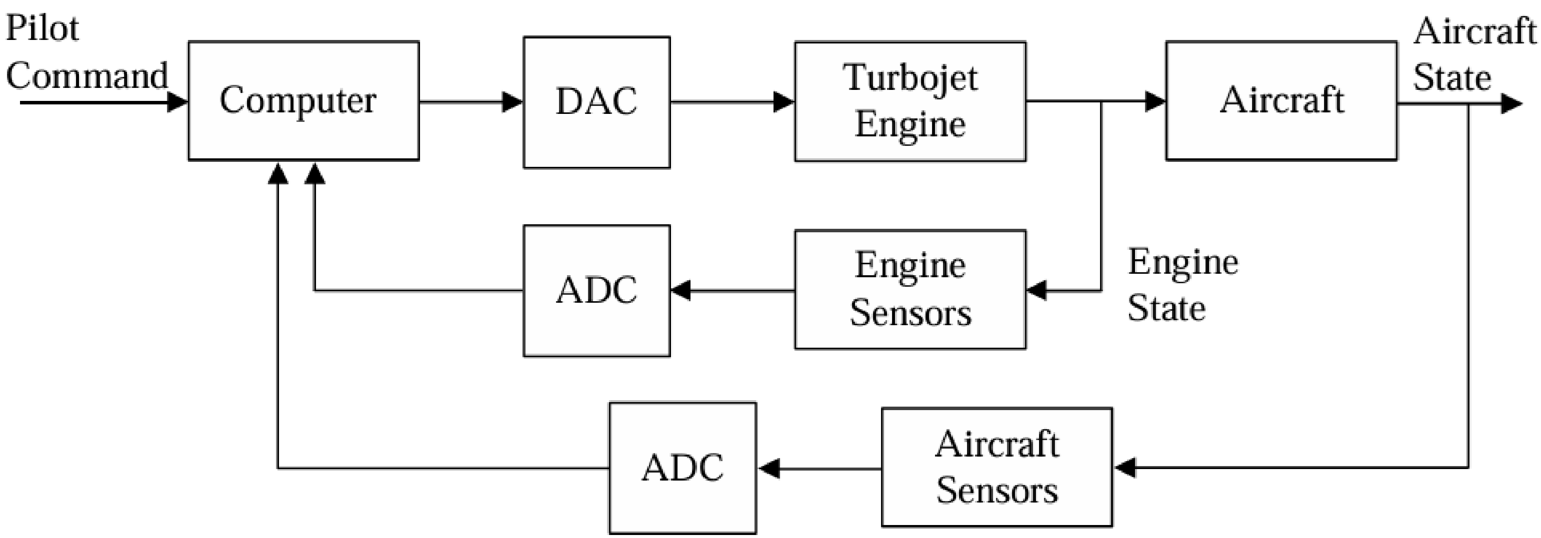
Example: Closed-loop drug delivery system

A sensor is used to measure the levels of the regulated drug or nutrient in the blood. This measurement is converted to digital form and fed to the control computer, which drives a pump that injects the drug into the patient's blood.



Example: Computer Control of an Aircraft Turbojet Engine:

Turbojet engines use sophisticated computer control strategies to achieve the high performance required for today's aircraft. Control requires feedback of engine condition (speed, temperature, and pressure), measurements of aircraft condition (speed and direction), and pilot command.



Example: Control of a robotic manipulator

Robotic manipulators are capable of performing repetitive tasks in manufacturing processes such as spot welding and painting. To perform their tasks accurately and reliably, manipulator positions and velocities are controlled digitally. Each motion or of the manipulator is positioned using a separate position control system. All the motions are coordinated by a supervisory computer to achieve the desired speed and positioning of the end-effector.