Course of "Industrial Automation"
2024/25

Introduction

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Course Administration

- **E-mail: francesco.montefusco@uniparthenope.it**
- **Books**
  - Introduction to Dynamic Systems: Theory, Models, and Applications, D. G. Luenberger. John Wiley & Sons.
  - Fondamenti di Controlli Automatici, 4th Ed , P. Bolzern, R. Scattolini, N. Schiavoni. McGraw-Hill (Italian).
  - Modern Control Engineering, 3rd Edition, K. Ogata, Prentice Hall, 2004.
  - Discrete-Time Control Systems, 2nd Edition, K. Ogata, Prentice Hall, 1995.
  - Digital Control of Dynamic Systems, 3rd Edition, G. F. Franklin, J. David Powell, M. Workman, Addison Wesley, 1998.
- **Slides of the lectures**
- **Prerequisites**
  - Main contents provided by the course of Automatic Control Systems.
- **Exam**
  - Written exam (in addition, ongoing written test – by the end of April).
  - Oral exam including discussion of a project report about the device of a closed-loop control system with required characteristics by using Matlab/Simulink

Contents of the course

- This course provides the methods to design industrial control systems and PID controllers

- The course is conceptually divided in three parts:
  - Discrete time systems
  - Notion of Industrial Automation
  - Design of digital control systems and PID implementation

- Laboratory activities

- After the course the student should be able
  - to analyse industrial control systems and evaluate the performance
  - to design closed-loop systems guaranteeing a set of these properties
  - to use software packages (Matlab and Simulink) to devise and evaluate control systems performance

Introduction

- Automation or automatic control is a discipline whose aim is the study of the methodologies and technologies able to reduce or completely eliminate the human intervention in applications of interest.

- Benefits:
  - Quality
  - Accuracy
  - Reliability
  - Repeatability
  - Cost reduction
  - Security
  - …

Applications

- Applications in most engineering domains:
  - Aerospace
  - Cars and Vehicles
  - Process industry
  - Energy storage and distribution
  - Home automation
  - Logistic
  - Biology
  - Autonomous systems and robots
  - …

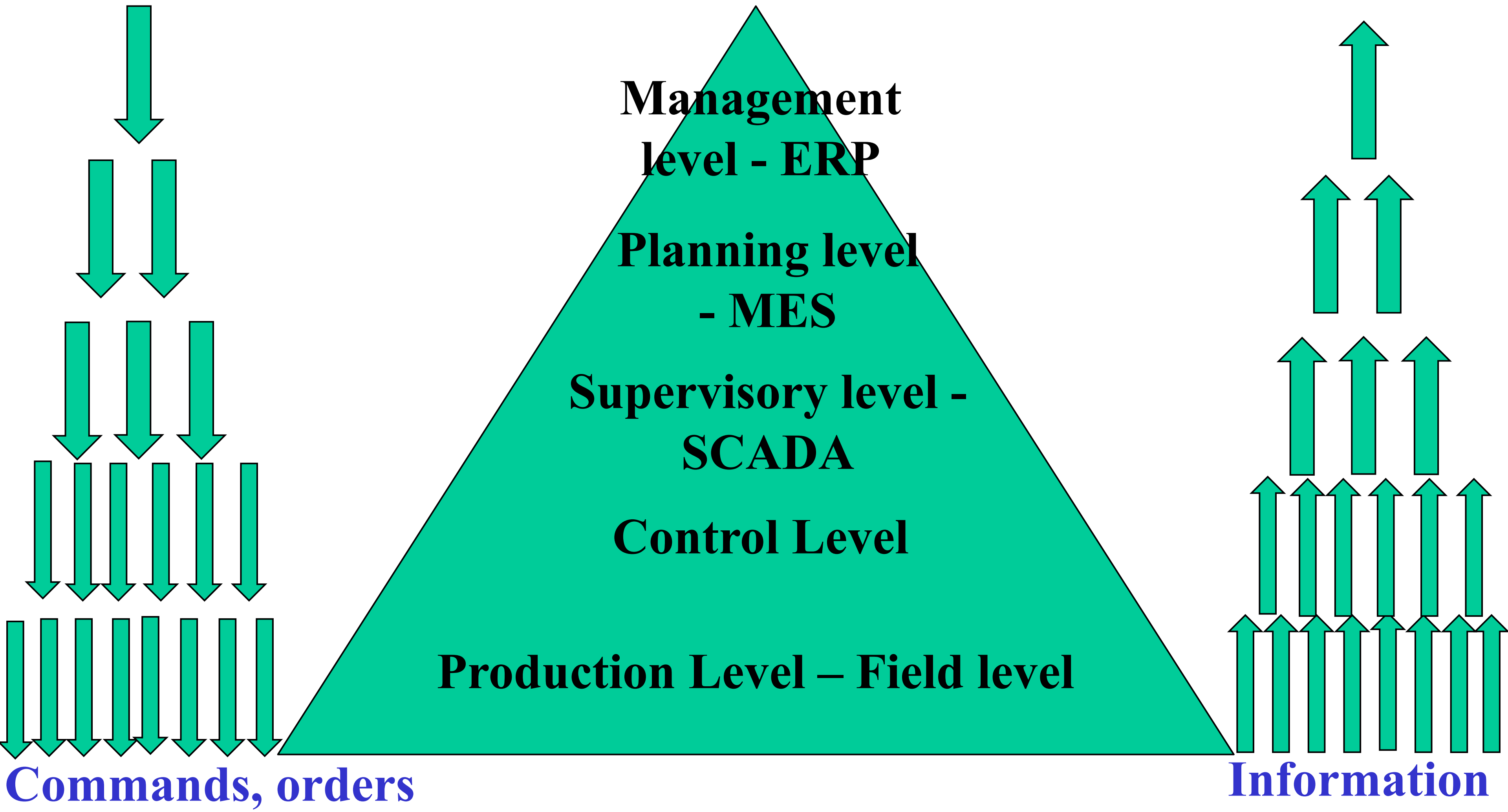
Detailed program of the course 1/2

- Introduction
- Discrete-time systems
  - LTI discrete time systems
  - Free and forced evolution
  - Stability
  - The Z-transform
- Notions of automatic control
  - Nominal and robust stability
  - Nyquist criterion
  - Requirements of a control system
- The root locus
  - Tracing of the root locus
  - Design of a control system using the root locus

Detailed program of the course 2/2

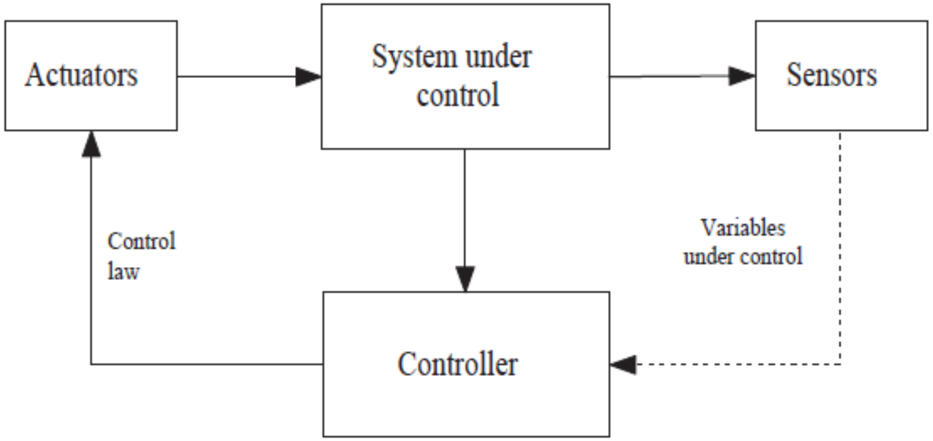
- Design of digital control systems
  - Analog-to-digital and digital-to-analog converters: their frequency characterization
  - Design through discretization of a time-continuous system. Design using the root locus
  - Control design in discrete time
- PID controllers and their implementation
  - PID controllers
  - Integral action anti-windup techniques
  - Bumpless transfer techniques
- Laboratory activities
  - Use of Matlab and Simulink for the design and verification of the behavior of closed loop systems

The Automation Pyramid is a hierarchical model of industrial automation systems…



(Local) control system at field level: components

An active control system (manual or automatic) can be logically divided in three parts:



Sensors:

whose aim is to measure the quantities of interest (related to the variables under control) in order to evaluate the behavior of the system under analysis

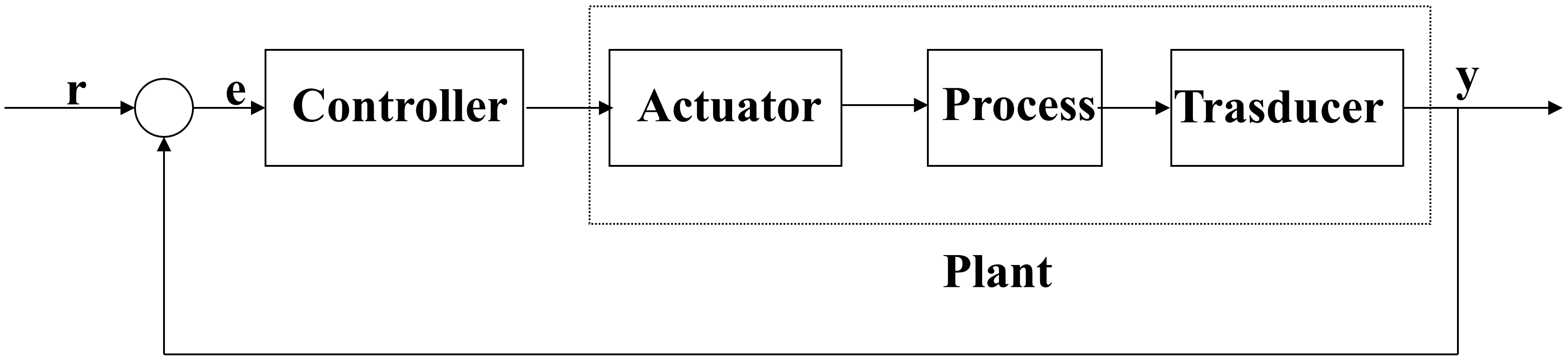
Controller:

whose aim is to impose the desired behavior to the system under control, making use of the values of the sensed variables (if available).

Actuators:

whose aim is to implement the computed control actions on a set of ***control variables*** (related but usually not coincident to the variables under control)

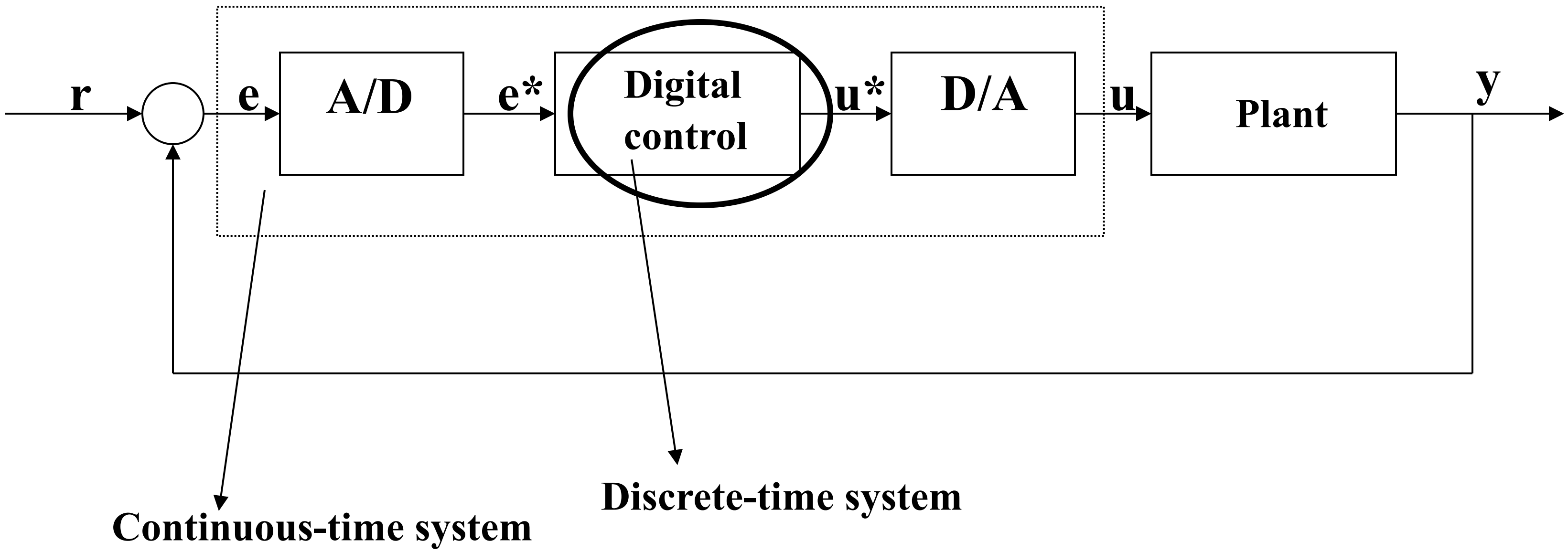
Continuous control system



Implementation of ***C*(*s*)**

- Past: analog electronic technology (op amps), hydraulic technology, pneumatic technology
- Present: digital technology (microprocessor systems)

Digital control system

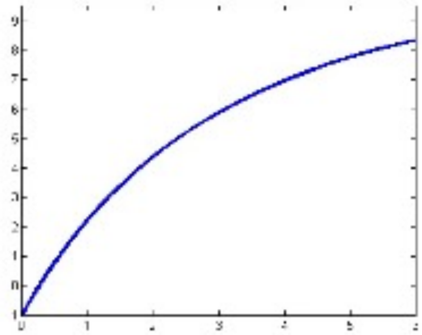


Implementation of ***C*(*z*)**

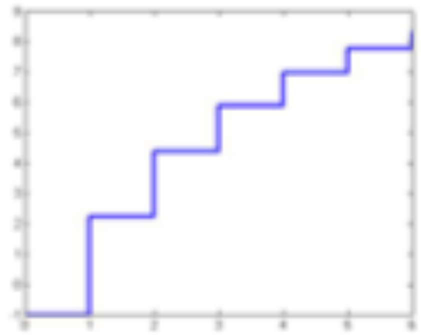
- ***C*(*z*)** is an algorithm (sums, products, . . .) that can be implemented in any programming language

Continuous-time signals

The time variable t varies continuously in an interval of $\mathbb{R}$.



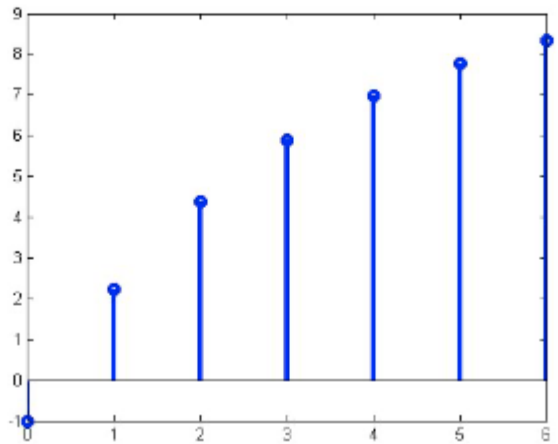
analog signals, if the amplitude can vary continuously in an interval of $\mathbb{R}$



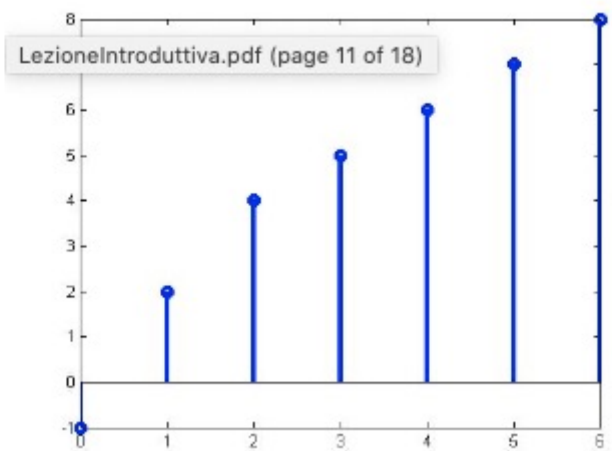
quantized signals, if the amplitude can assume only a finite set of values

Discrete-time signals

The time variable can assume only a set (even infinite) of discrete values.



sampled data signals, if the amplitude can vary continuously in an interval of $\mathbb{R}$



digital signals, if the amplitude is quantized.

Digital signals are represented with a finite number of binary digits.

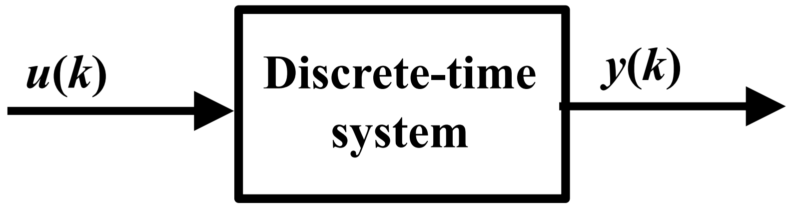
Discrete-time systems

- Discrete-time systems are characterized by the fact that the time variable is integer rather than real.

- So, input and output are sequences of numbers,

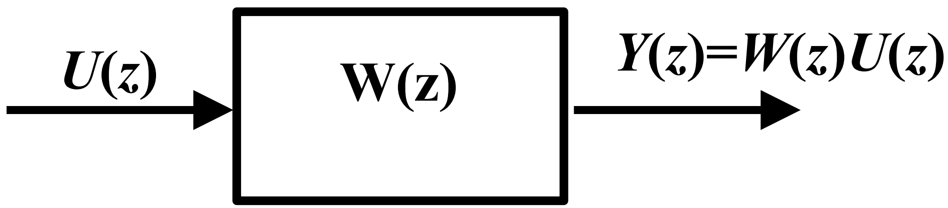
$$\{u(k)\}_{k\in N} \qquad \{y(k)\}_{k\in N}$$

- … and are denoted by $u(k)$ and $y(k)$.



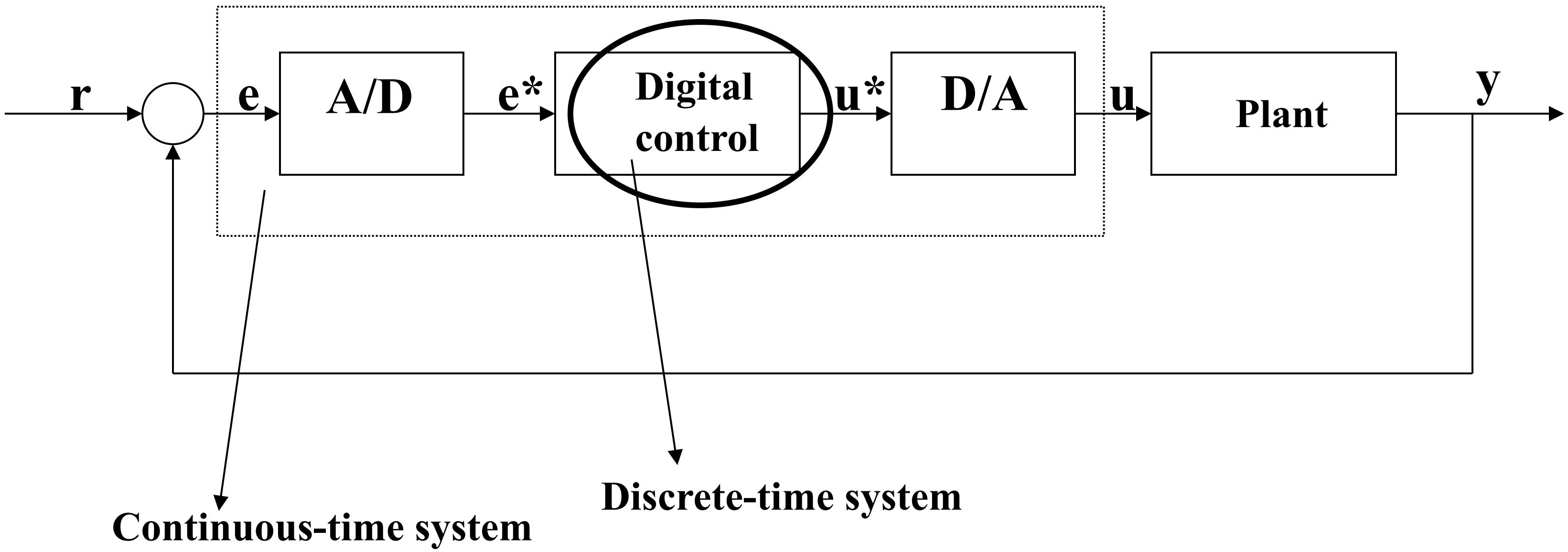
The Z-transform of $f(k)$**:** $F(z) = Z\big(f(k)\big) = \sum_{k=0}^{+\infty} f(k) z^{-k}$

The transfer function W(z)



$$W(z) = \frac{Y(z)}{U(z)}$$

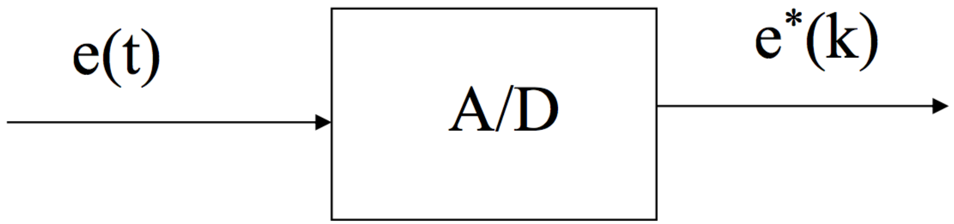
Digital control system



Analog-to-digital converter (ADC, A/D, or A-to-D)

- The digital controller is a discrete-time system and the plant to be controlled is a continuous-time system.

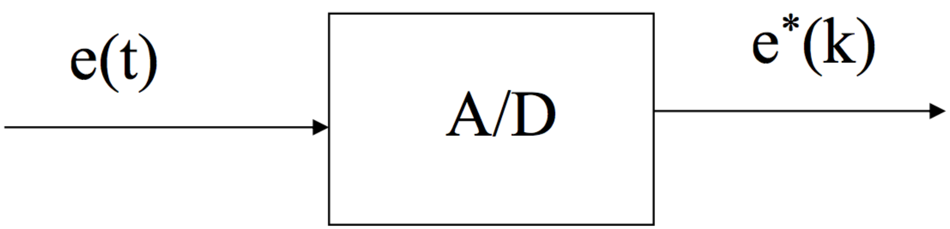
- It is needed a device that transforms a continuous signal into a discrete one.



- Such device is the analog-to-digital converter (A/D).

Ideal sampler

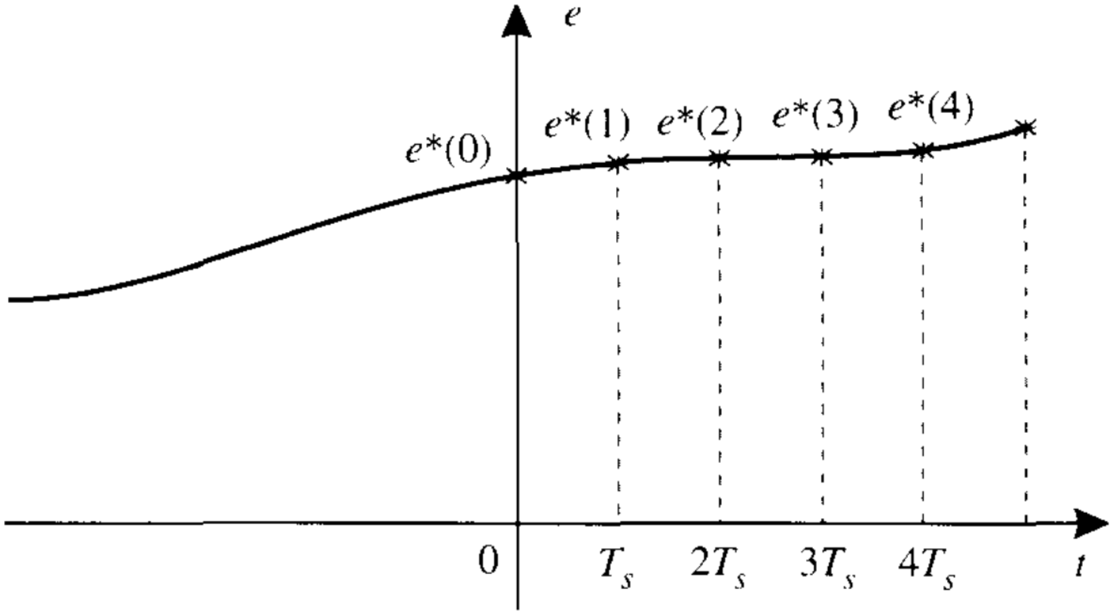
- The most common analog-to-digital converter is the sampler, which does the following

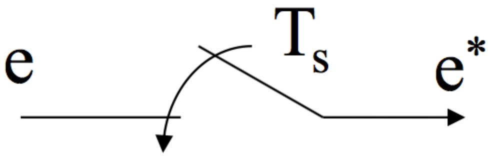


$$e^{*}(k) = e(kT_s)$$

- Periodic sampling: the sampling instants are equally spaced, or k, i.e. $t_k=kT_s$ (k=0,1,2,..), with T_s representing the sampling time.
- The hold circuit holds the value of the sampled signal over a specified period of time.

Sampling operation





- $f_S = \frac{1}{T_S}$
- $\omega_S = 2\pi f_S = \frac{2\pi}{T_S}$.

Sampling operation

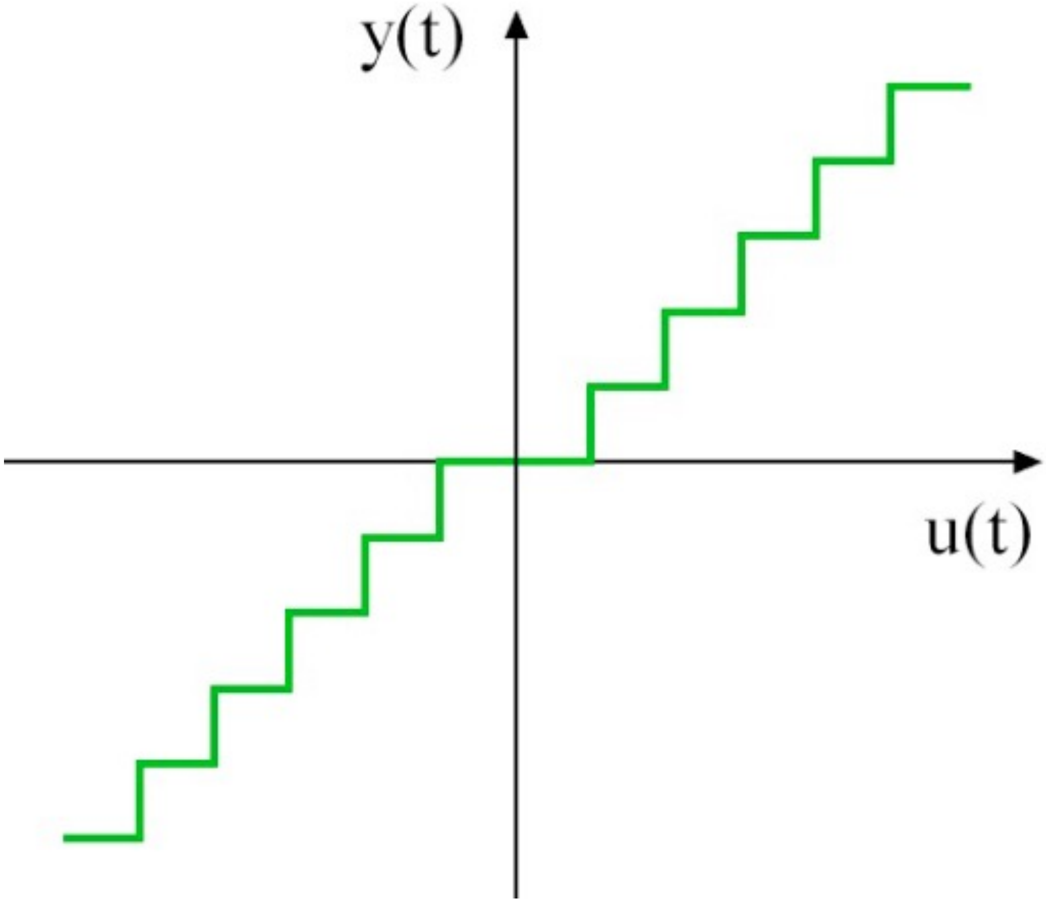
- The common problem when sampling a signal is the loss of information.

- Indeed, it is obvious that the same signal $e^*(k)$ can be generated by infinite continuous-time functions $e(t)$.

- Hence, given a signal $e^*(k)$ it is impossible to go back to the original signal $e(t)$.

Quantization

- The sampler defined above is ideal.
- It is assumed that in the sampling instants the value of e^* coincides with that of e.
- $e^*(k)$ is represented by a finite number of discrete states (by a numerical code)
- The process of representing a continuous or analog signal into a set of discrete state is called (amplitude) quantization.
- The output state of each quantized sample is then described by a numerical code (such a binary code): this process is called encoding.



- The standard number system used for processing digital system is the binary number system
- n bits available, 2^n amplitude levels represented
- The quantization operation introduces a nonlinearity in the system
- When the number of digits of the binary representation is high enough, it is possible to neglect the effect of quantization

Digital-to-analog converter (DAC, D/A, or D-to-A)

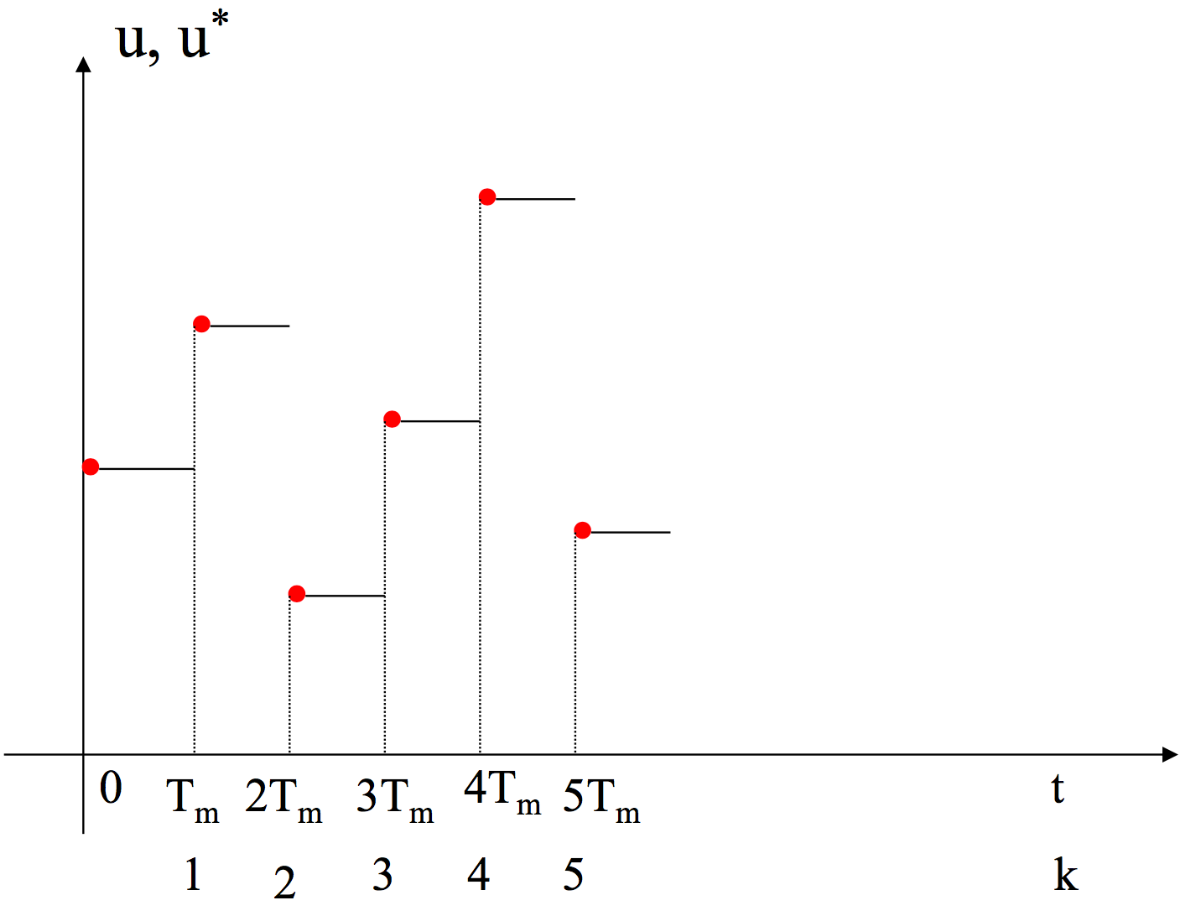
- It is a device that transforms a digital input (binary numbers) to an analog output.

- The most commonly used D/A converter is the zero order hold (ZOH), which operates as follows:

$$u(t) = u^{*}(k) \quad t \in \left[kT_m, (k+1)T_m\right]$$

- T_m is the sample time

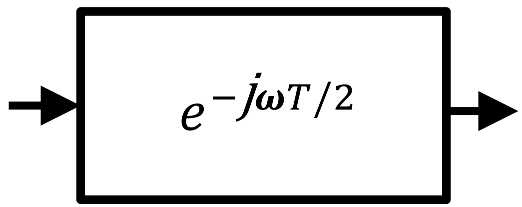
ZOH circuit



In order for an analog signal ($e(t)$) to be reconstructed from its sampled version ($e^*(k)$), by Shannon's theorem, it must have a strictly limited bandwidth and $\omega_S > 2\omega_B$ (with ω_B signal bandwidth).

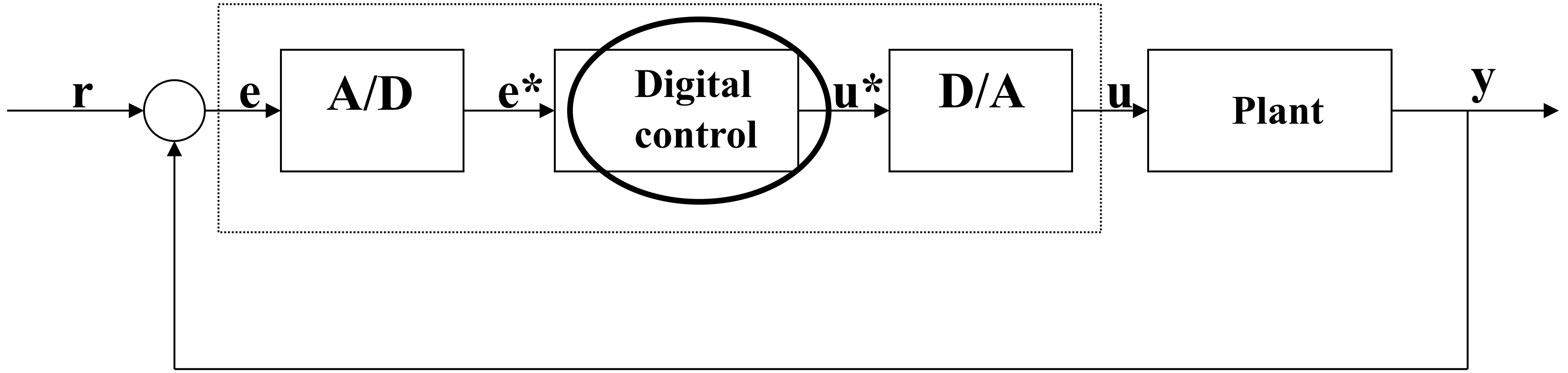
Sampler – ZOH series

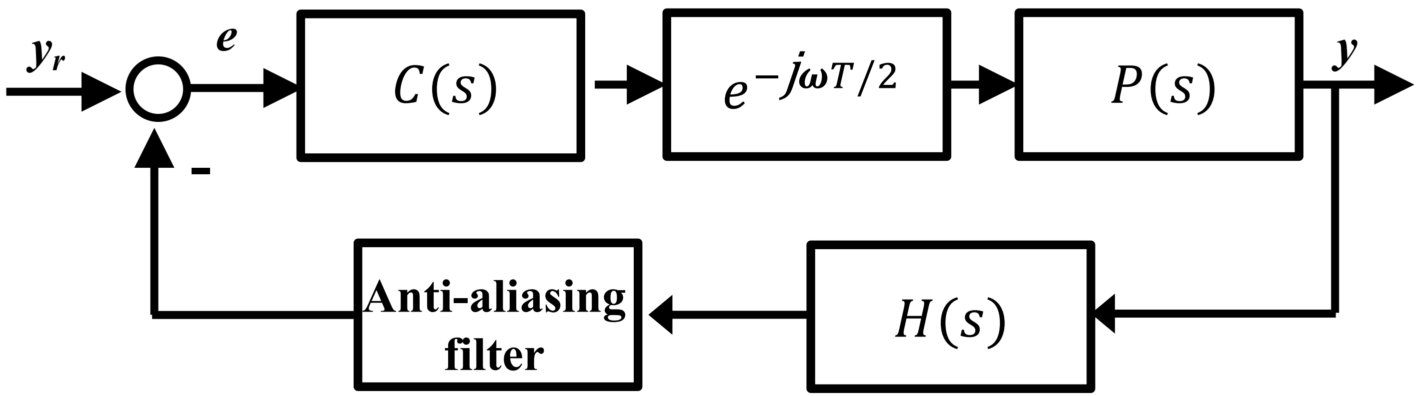
- By working in the frequency range $\omega < \frac{\omega_S}{8}$, it is possible to approximate the sampler-zoh series (hp $\boldsymbol{T_s}=\boldsymbol{T_m}=\boldsymbol{T}$) with a delay element



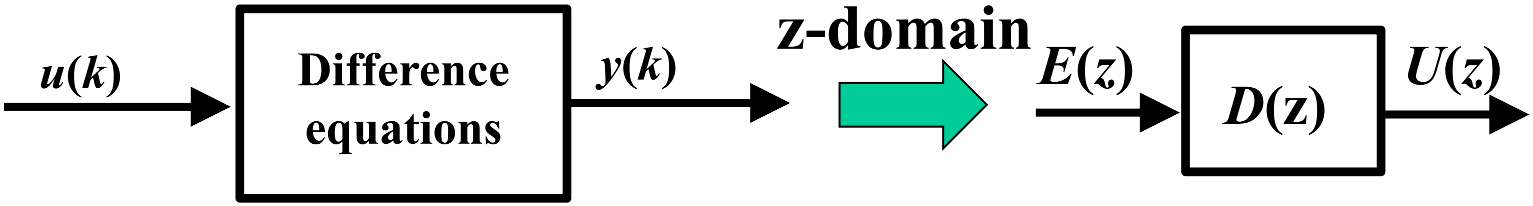
- where this term introduces a maximum delay equal to $\frac{\omega T}{2}\Big|_{\omega=\frac{\omega_S}{8}} \approx 22°$
- The presence of a numerical control tends to destabilize the entire system.

Scheme of the digital control system in continuous-time





Analog vs. digital



- From $C(s)$ we want to find an equivalent $D(z)$:

- The transition from continuous time to discrete time is expressed by the following equality:

$$z = e^{sT}$$
$$C(s)|_{s=j\omega} = D(z)|_{z=e^{j\omega T}}$$

- By Euler's method,

$s = \frac{z-1}{T}$ (forward rectangular rule) and $s = \frac{z-1}{zT}$ (backward).

- Bilinear transformation: $$s = \frac{2}{T}\frac{z-1}{z+1}$$

- The presence of a numerical control tends to destabilize the entire system.

$U(z)=D(z)E(z)$.