DIPARTIMENTO DI
INGEGNERIA ELETTRICA
E DELL'INFORMAZIONE

POLITECNICO
DI BARI

Introduction to Digital Control Systems

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Summary

Brief historical perspective on digital control systems

Digital control systems vs Analog control systems

Some applications of digital control systems

Typical digital control schemes

Signals sampling, conversion, reconstruction

Control algorithms

Synthesis of discrete time control systems

Digital control systems

Why digital control systems

Digital control systems make functions possible that could not be performed without (embedded) digital computers

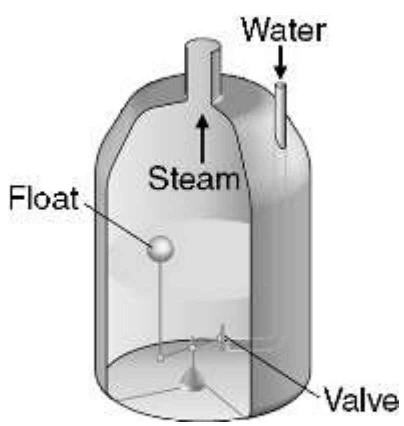
The introduction of digital control systems has enabled the synergistic integration of design, analysis, optimization, and virtual prototyping of intelligent and high-performance electromechanical systems, system intelligence, learning, adaptation, decision making, and control through the use of advanced hardware (actuators, sensors, microprocessors, DSPs, power electronics, and ICs) and leading-edge software.

Historical perspective

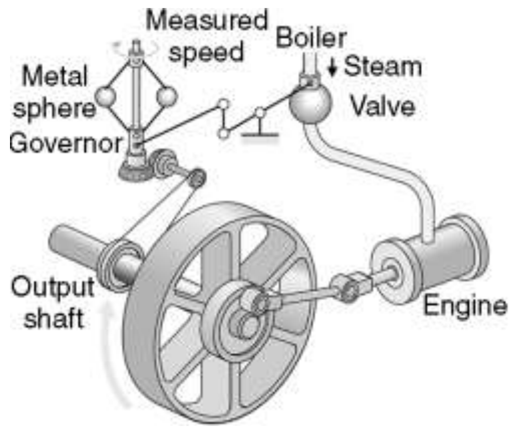
Industrial revolution allowed design of products and processes for energy conversion and transmission thus enabling the use of energy to do useful work

First developments of automated mechanical systems

- **The first historical feedback system is the Polzunov's water-level float regulator**
- **Further evolution in automation enabled by advancements in control theory traced back to the Watt flyball governor of 1769**



Water-level float regulator



Watt's flyball governor

Historical perspective

Engineering designs of this era were largely mechanical

- **operations of motion transmission, sensing, actuation, and computation were performed using mechanical and hydraulic systems**

Such systems suffered from

- **Power amplification inability**
- **Energy losses due to tolerances, inertia, and friction**

The next step in the evolution of automation required a theory of automatic control

- **The basic idea of controlling a mechanical system automatically was firmly established by the end of 1800s.**
- **The evolution of automation would accelerate significantly in the twentieth century**

Historical perspective

Advances in development of pneumatic control elements in the 1930s enabled the application in the process industries

- Early control systems design characterized by trial-and-error methods
- Advances in mathematical and analytical methods solidified the notion of control engineering as an independent engineering discipline

The development of electronic feedback in the frequency domain for telephone systems by Bode, Nyquist, and Black at Bell Telephone Laboratories defined the design and analysis practices which are now generally classified as *classical control*

Historical perspective

Advances in automatic control theory and practice due to World War II war efforts

- Design and construction of automatic airplane pilots, gun-positioning systems, radar antenna control systems, and other military systems
- Extension of the available control techniques and fostered interest in control systems and the development of new insights and methods
- Frequency domain approaches, increased use of the Laplace transform, and the use of the so-called s-plane methods (e.g. root locus)

During the 1950s, the invention of the cam, linkages, and chain drives became the major enabling technologies for the invention of new products and high-speed precision manufacturing and assembly

Historical perspective

Semiconductor Revolution led to the creation of integrated circuit (IC) technology

- Effective, miniaturized, power electronics could amplify and deliver needed amount of power to actuators.
- Signal conditioning electronics could filter and encode sensory data in analog/digital format.
- Hard-wired, on-board, discrete analog/digital ICs provided rudimentary computational and decision-making circuits for control of mechanical devices.

Historical perspective

The introduction of digital technologies in the late 1950s brought enormous changes to automatic control.

Supervisory systems as first applications of digital computers to process control - individual loops controlled by conventional electrical, pneumatic or hydraulic controllers, but monitored and optimized by computer:

- 1959: Texaco Port Arthur (Texas) refinery
- 1960: Monsanto ammonia plant at Luling (Louisiana)

They quickly recognised the potential of the newly emerging digital technology to i**mprove the recording and displaying of plant information, not as a means of providing automatic control**

Historical perspective

Direct digital control (DDC) and supervisory control in the 2nd half of the 1960s

- Discrete form of a control algorithm (e.g. PID control)
- Expensive implementations and many programming problems

In the late 1960s, the development of the microprocessor led to early forms of computer control in process and product design

- New time domain methods (Liapunov, Minorsky, and others) and optimal control theories (Pontryagin and Bellman)
- Numerically controlled (NC) machines
- Aircraft control systems
- Manufacturing processes still entirely mechanical in nature… Automation and control systems are only an afterthought!

Historical perspective

The use of microprocessor and digital computers allowed the real implementation of the more advanced control techniques that were being developed in the '60s and '70s

During the 1980s, the utilization of digital computers as integral components of control systems became routine

Advent of the space age provided yet another impetus to the continued development of controlled mechanical systems

- Development of complex, highly accurate control systems for Missiles and space probes
- Development of optimal control, related to the need to minimize fuel consumption while providing accurate control

Historical perspective

The semiconductor revolution

Advancements in semiconductor and integrated circuits manufacturing led to the development of a new class of products that incorporated mechanical and electronics in the system and required the two together for their functionality (Mechatronic Systems)

The Information technology revolution

Development of VLSI technology led to the introduction of microprocessor, microcomputer, and microcontroller: computing hardware became ubiquitous, cheap, and small

Historical perspective

As computing hardware can be effortlessly interfaced with real world electromechanical systems, it is now routinely embedded in engineered products/processes for decision-making

- Microcontrollers are replacing precision mechanical components, e.g., precision-machined camshaft that in many applications functions as a timing device.
- Programmability of microcontrollers is providing a versatile and flexible alternative to the hard-wired analog/digital computational hardware.
- Integrated devices are now capable of converting, transmitting, and processing both the physical energy and the virtual energy (information).

Digital control systems
vs
Analog control systems

Digital vs Analog Control Systems

What advantages are there to replacing analog components with a digital computer?

- **Increased computing power and accuracy**
  - More sophisticated control algorithms
  - Complex mathematical function easily implemented on a digital calculator rather than with an operational amplifier circuit or, even worse, by a system built with hydraulic or mechanical elements
  - Control of non-measurable variables (e.g., for automotive applications, tire slip, internal tensions or temperatures, slip angle and ground speed of vehicles, damping parameters)
- **Flexibility in response to design changes**
  - Future changes or modifications in the control algorithms can be implemented with simple software changes rather than expensive hardware modifications
  - Programmable functions allow changes during design, commissioning and after-sales, and shorter time-to-market
  - Flexible adaptation to changing boundary conditions

Digital vs Analog Control Systems

What advantages are there to replacing analog components with a digital computer?

- **Noise immunity and more reliable signal transmission**
  - Digital systems exhibit more immunity and less sensitivity to noise and disturbances than analog systems by virtue of the methods of implementation
  - Errorless long-distance transmission, due to encoding of signals
  - Disturbances at mains frequency from power systems are canceled

- **Increased reliability and repeatability**
  - No signs of ageing, thermal drift, environmental factors, etc.
  - Fault-tolerant systems with hardware and analytical redundancy

Digital vs Analog Control Systems

What advantages are there to replacing analog components with a digital computer?

- **Reduction of complexity of monitoring system and hardware**
  - Banks of equipment, meters, and knobs are replaced with computer terminals
  - Information about settings and performance is obtained through menus and screen displays
  - Teleservice functions for monitoring, maintenance, repair
  - Integrated advanced supervision and fault diagnosis
- **Cost-effective solution for control systems**
  - The costs of MPs and DSPs are continuously going down.
  - Digital processors are more compact and lightweight. Single-chip MPs and DSPs can be made very versatile and powerful for control applications, resulting in cost reduction.

Digital vs Analog Control Systems

What disadvantages are there to replacing analog components with a digital computer?

- **More complex design procedure, calling for special skills on:**
  - Digital control systems design
  - Programming and embedded computing
  - Interfacing
  - Embedded real-time networking
  - ... and so on
- **Possible unexpected stops**
  - It is not possible to foreseen all possible error situations when developing the control and supervision software
- **Need of electrical power**
  - Digital control systems always include electronic equipment: their use is contraindicated in critical environments where explosions could occur

Digital vs Analog Control Systems

What disadvantages are there to replacing analog components with a digital computer?

- **More precarious stability**
  - Loss of information and discontinuity in transmission due to sampling.
  - Limitations on computing speed and signal resolution due to the finite word-length of the digital processor. In contrast, analog controllers operate in real time, and the resolution is theoretically infinite. The finite word-length of the digital processor often translates into system instability in the form of limit cycles in closed-loop systems.
  - Delays and latencies introduced by the computation time. The limitation on computing speed causes time delays in the control loop which may cause instability in closed-loop systems.
  - Crucial role of sampling period

Typical digital control schemes

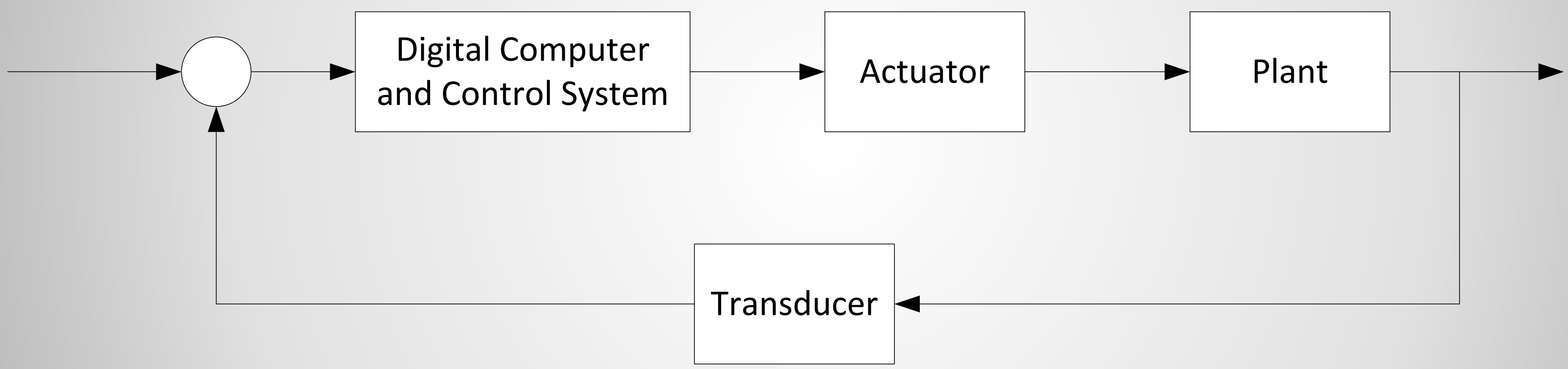
Signals and interfaces in digital control systems: sampling, conversion, reconstruction

Digital control schemes

Where then is the computer placed in the loop?

Its position in the loop depends upon the function it performs (the controlled loop).

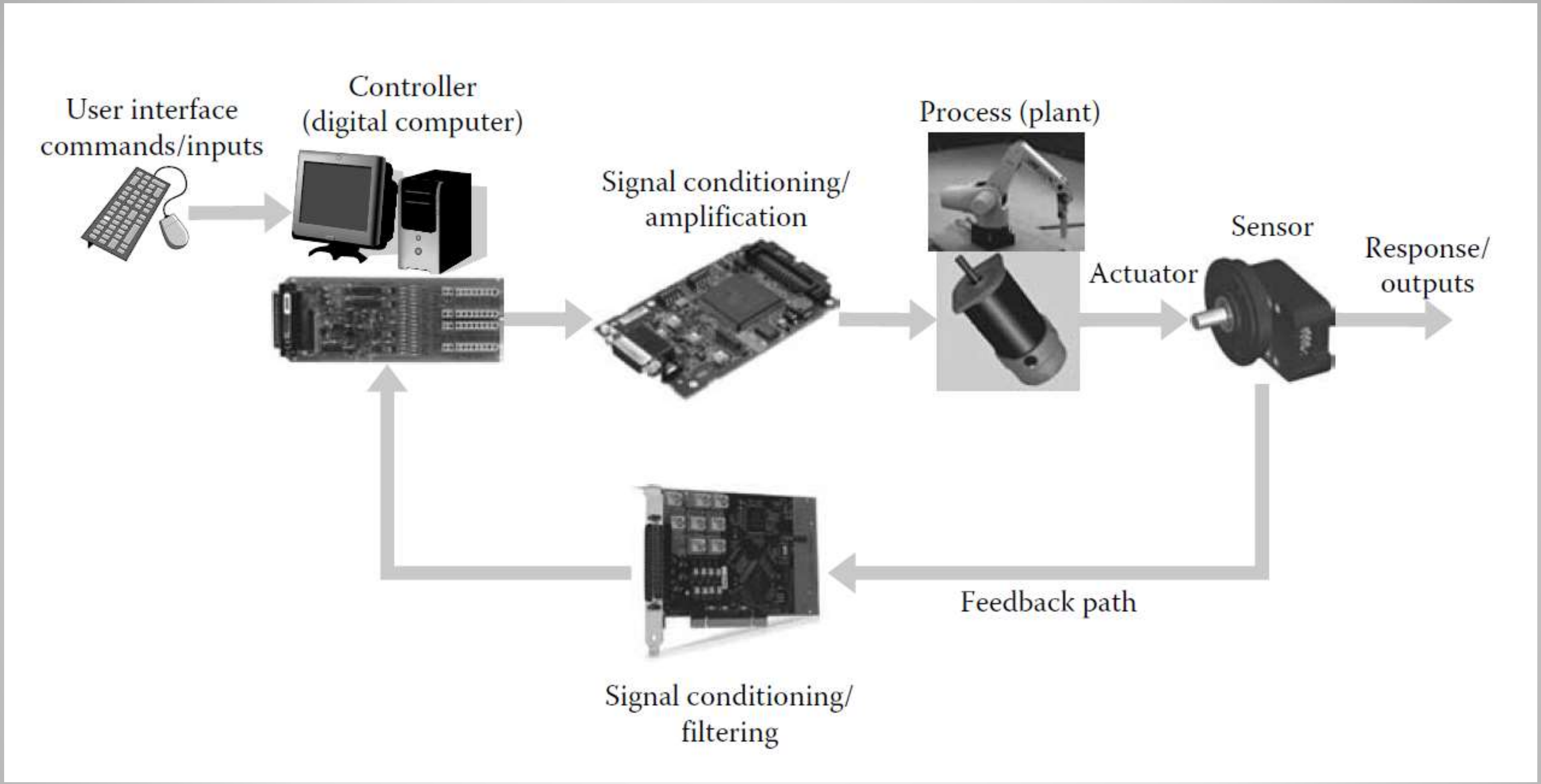
Typically, the computer replaces the cascade compensator



Placement of the digital computer within the loop

A simplified block diagram

Digital control schemes



Placement of the digital computer within the loop

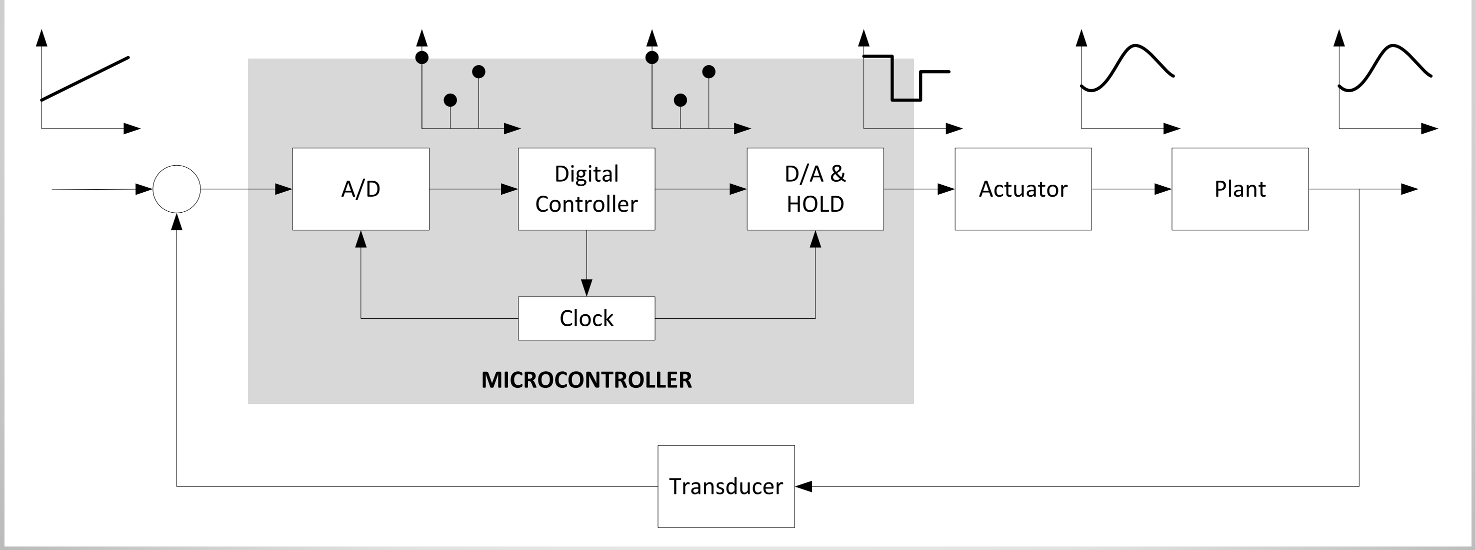
Actual block diagram

Sampled-data systems

Signals can take on two forms: digital or analog.

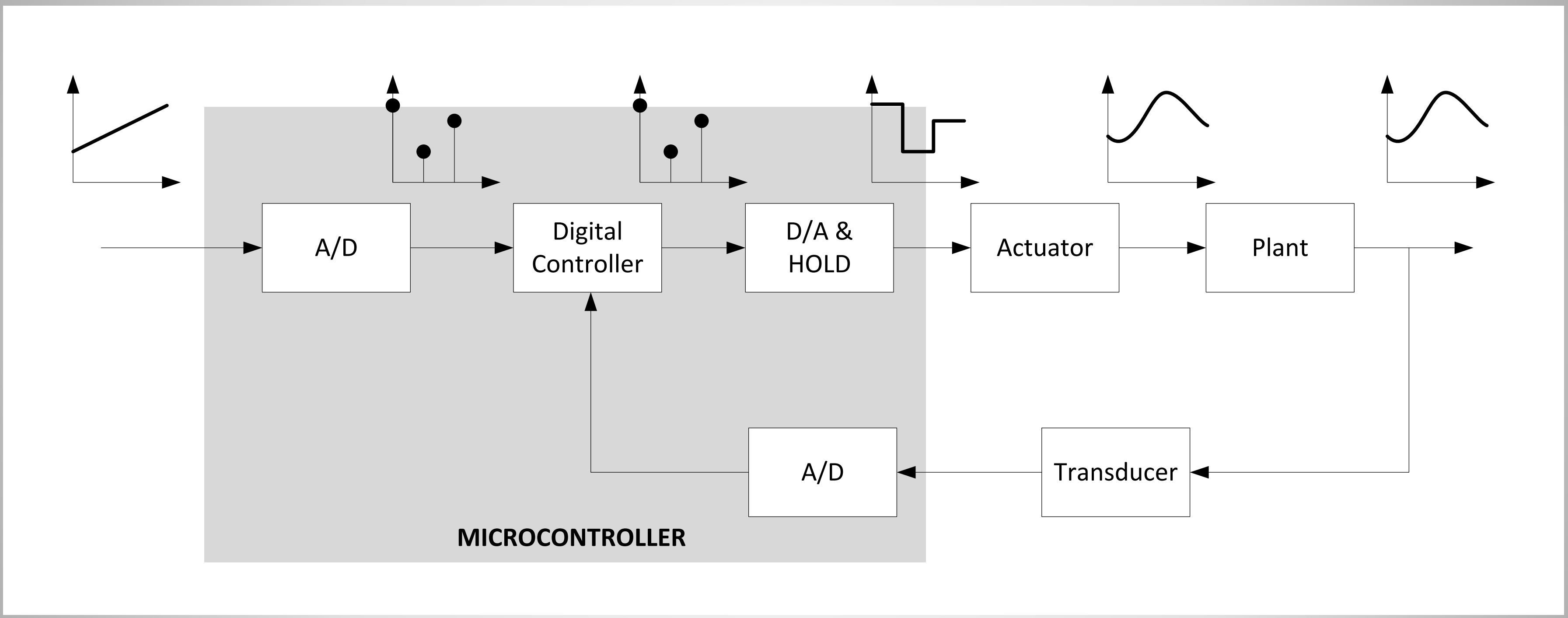
Means of conversion form one form to the other are needed in loops containing both analog and digital signals

- Analog-to-digital (A/D) converter (must be provided at the input to the digital computer)
- Digital-to-analog (D/A) converter (must be provided at the output of the digital computer).



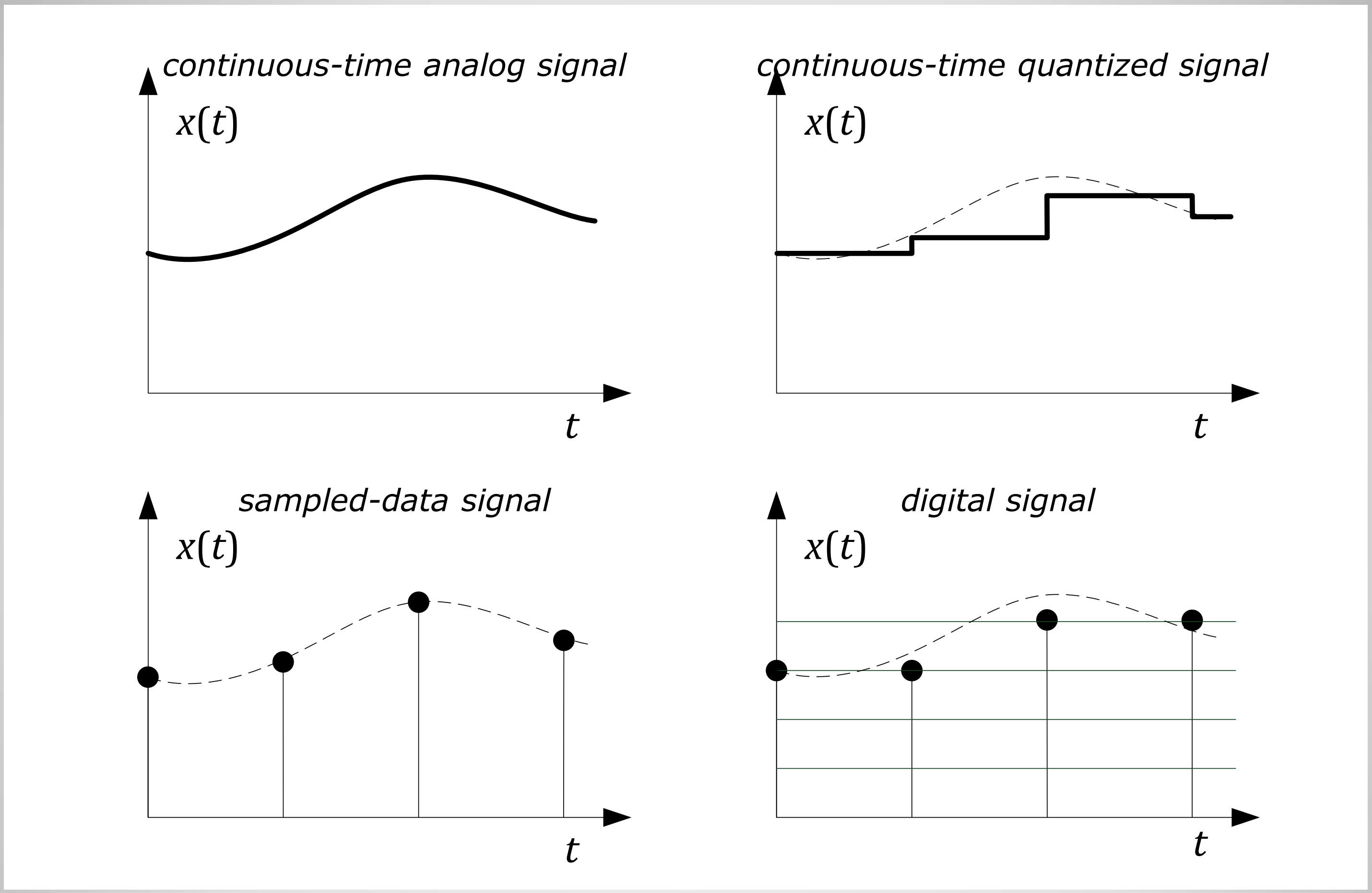
A digital feedback control system

Sampled-data systems



A digital feedback control system – Alternative scheme

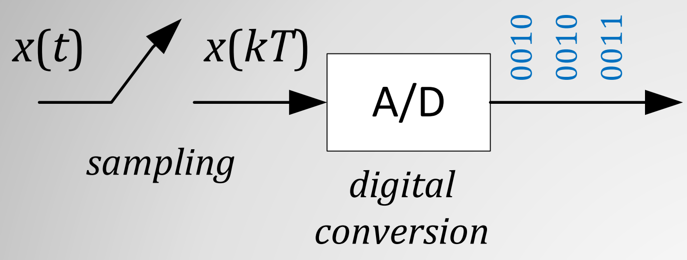
Sampled-data systems

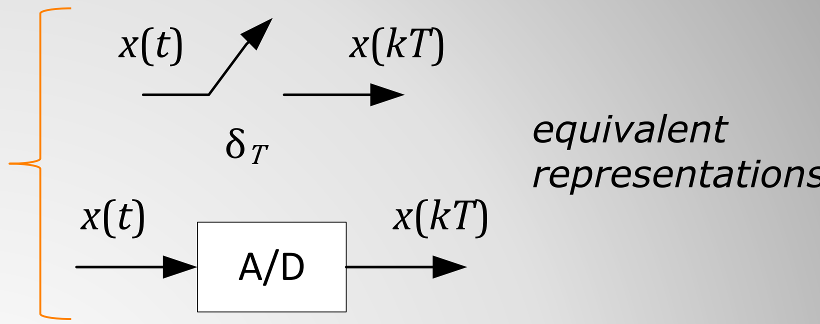


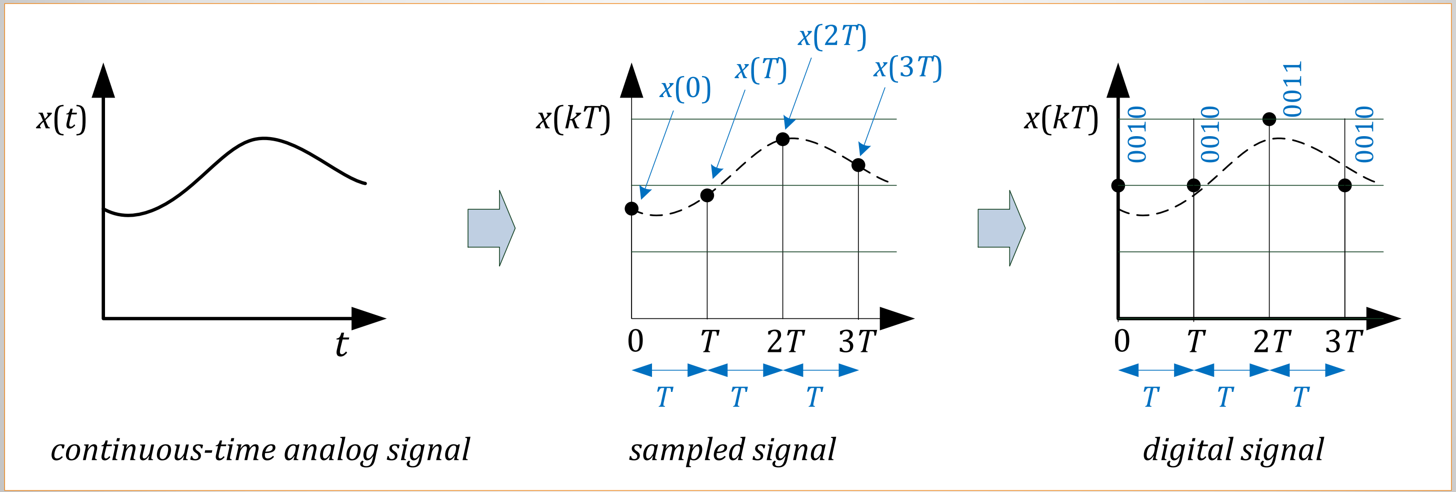
Signals in a digital feedback control system

A/D conversion

A/D Converter





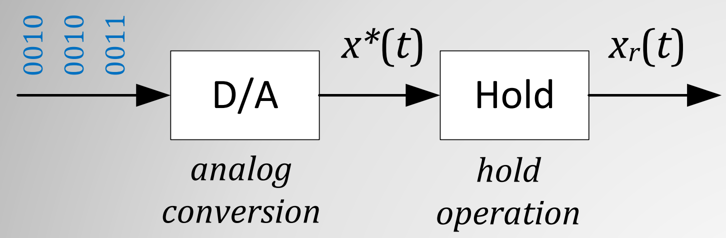


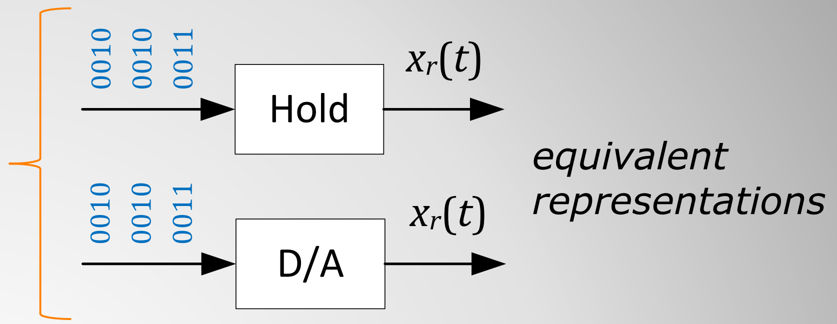
Two main operations:

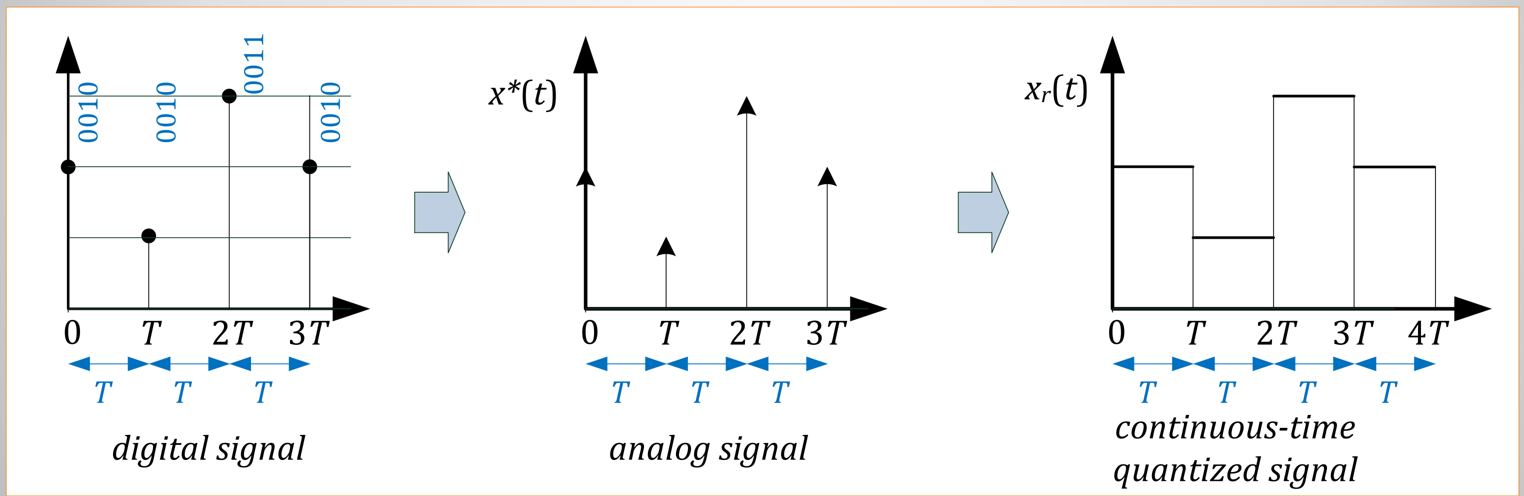
- Sampling
- Quantization and digital conversion

D/A conversion

D/A Converter







Two main operations:

- Analog conversion
- Signal reconstruction (hold operation)

Control algorithms

The control algorithm is usually implemented in the form of a finite difference equation

$e(k)$ error signal at sampling time kT

$u(k)$ output of the controller at sampling time kT

$$u(k) = b_0 e(k) + b_1 e(k-1) + \cdots + a_1 u(k-1) + a_2 u(k-2) + \cdots$$

Please note that if, for the considered control algorithm, $u(k)$ directly depends on $e(k)$, the computation time of $u(k)$ should be negligible

Control algorithms

The controller algorithm in a computer is implemented as a program which runs continuously in a loop which is executed at the start of every sampling time.

Inside the loop, the following operations are performed continuously:

- Read the desired value R from A/D converter
- Read the actual plant output Y from the A/D converter
- Calculate the error signal $E = R - Y$
- Calculate the controller output U for the current sampling instant
- Send the controller output to D/A converter
- Wait for the next sampling instant

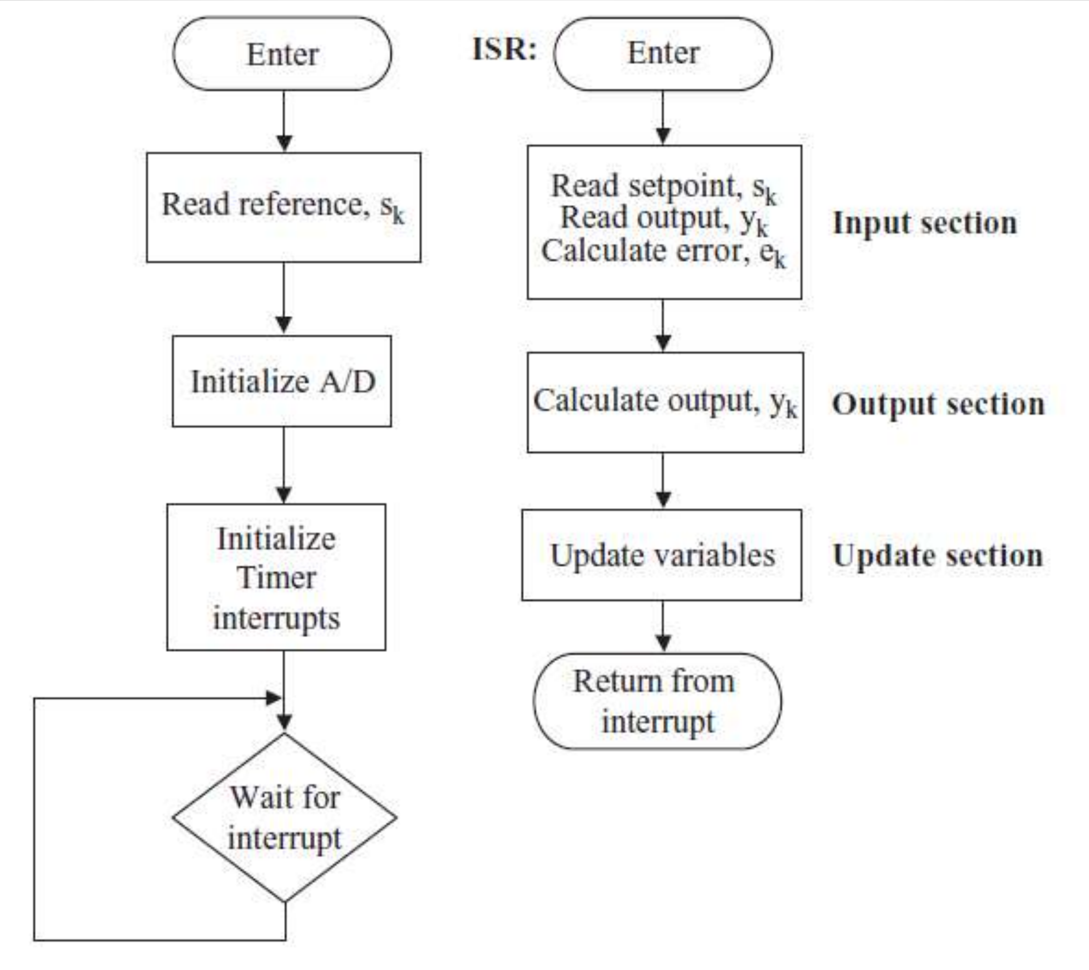
Control algorithms

Once it has been started, **the algorithm must run continuously** and **exactly at the same times** (i.e. exactly at the sampling instants), until some event occurs to stop it or until is stopped manually by an operator.

The synchronization can be achieved in several ways:

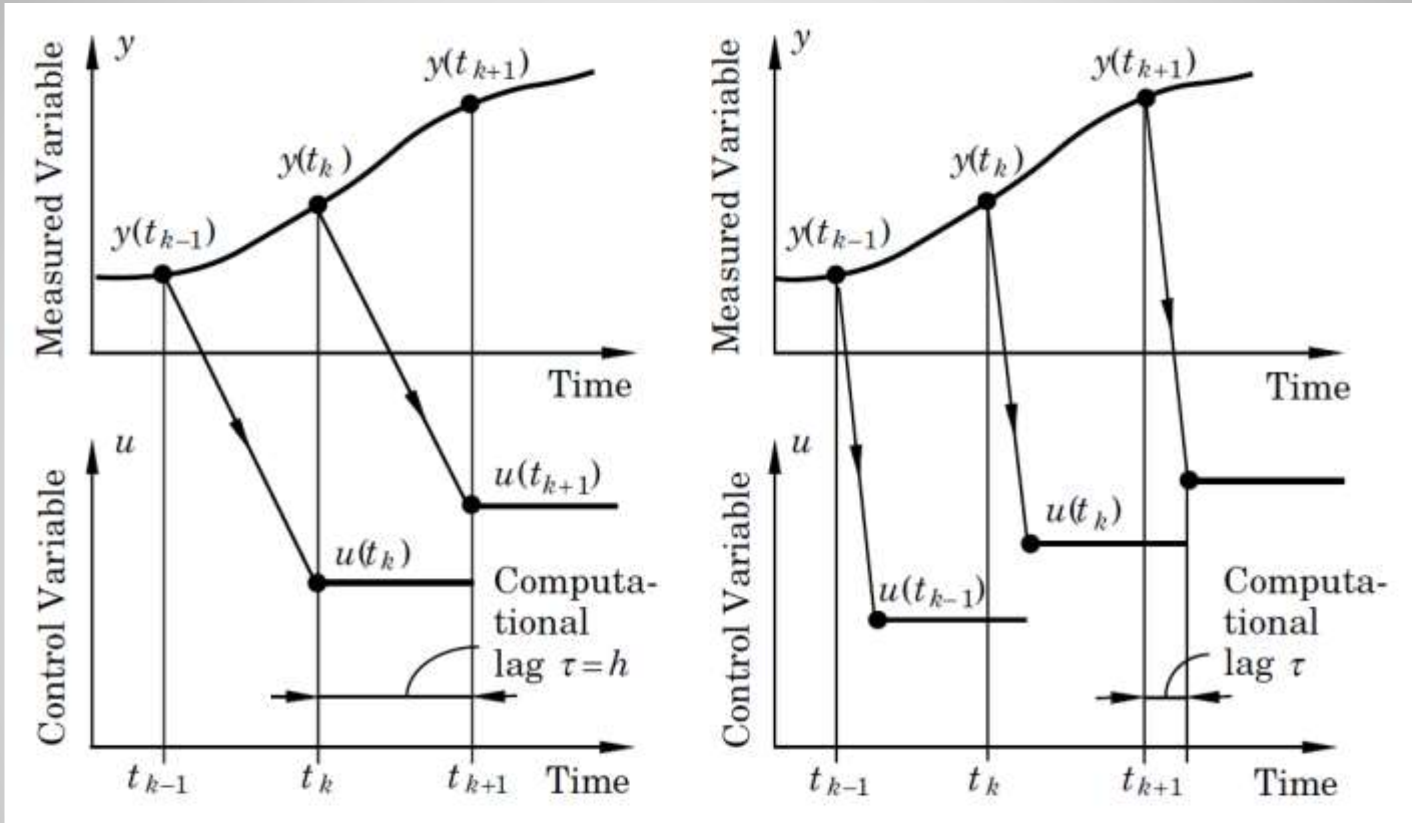
- using external interrupts for timing (e.g. by an external clock)
- using timer interrupts
- using an external real-time clock

Control algorithms



Controller implementation by using an ISR
Main program and interrupt service routine

Control algorithms



Two ways of synchronizing inputs and outputs. On the left, the signals measured at time t_k are used to compute the control signal to be applied at time t_{k+1}. On the right, the control signals are applied as soon as they are computed.

Control algorithms

The software requirements in a control computer can be summarized as follows:

- the ability to read data from input ports
- the ability to send data to output ports
- internal data transfer and mathematical operations
- timer interrupt facilities for timing the controller algorithm

All of these requirements can be met by most digital computers, and, as a result, most computers can be used as controllers in digital control systems.

A proper and cost effective choice of the equipment is related to the required computational effort

Synthesis of discrete time control systems

Direct techniques (z-plane design, or direct digital design)

1. Plant model (+hold) discretization
2. Perform the design using only the discrete representation
   - Root locus
   - Frequency domain
   - Deadbeat design
   - Analytical design
   - Dahlin algorithm
   - ...

Synthesis of discrete time control systems

Indirect techniques (transform technique, emulation, or s-plane design)

1. Design the continuous-time controller in the s-domain, using well-known classical techniques (e.g. root-locus, frequency domain, etc.)
2. Calculate the discrete-time equivalent controller by using a discretization technique
   - First backward difference
   - First forward difference
   - Tustin transformation
   - Tustin transformation with prewarp
   - Poles-zeros equivalence
   - Invariance in impulse and step response
   - ...

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