Device Architecture

ΕΠΛ 428: IOT PROGRAMMING

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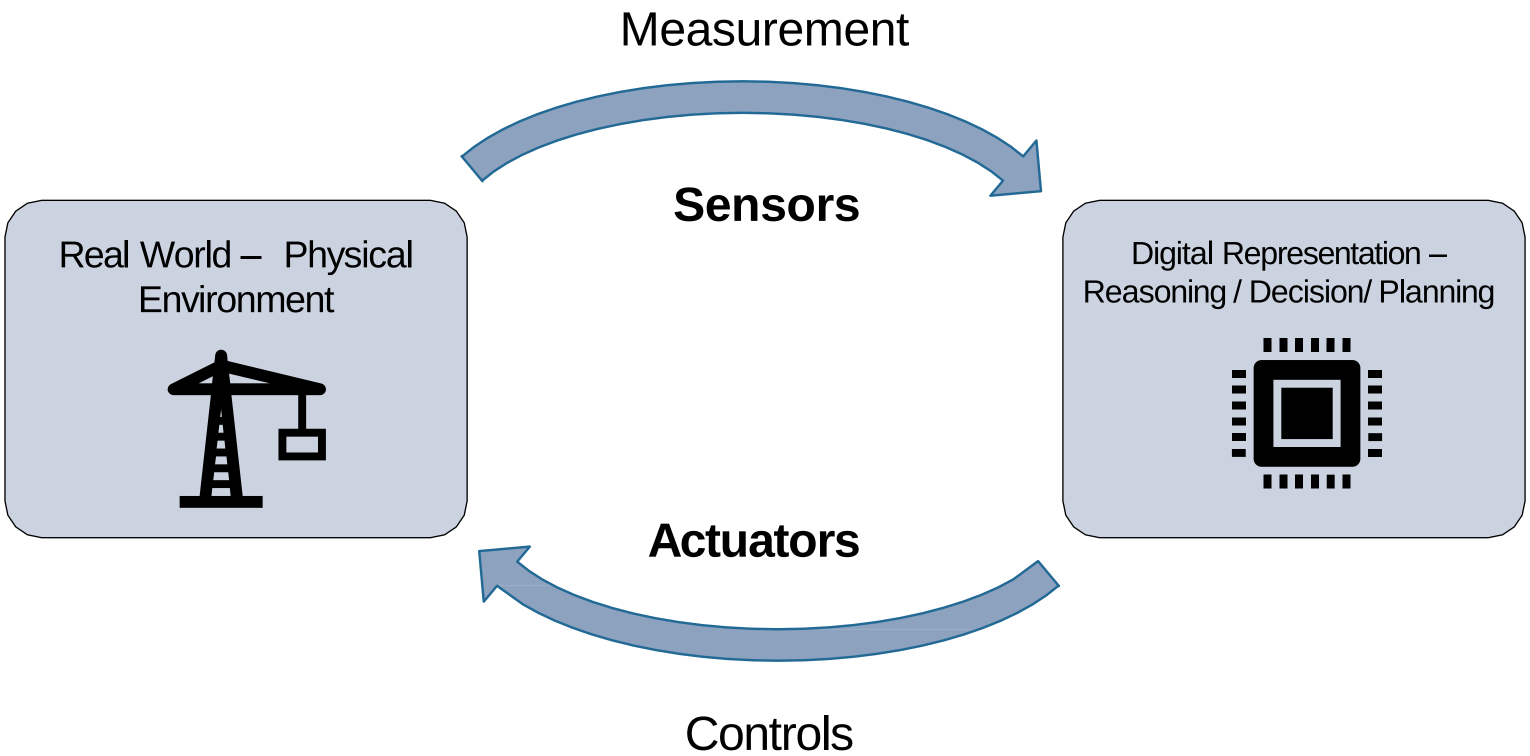
Πανεπιστήμιο Κύπρου



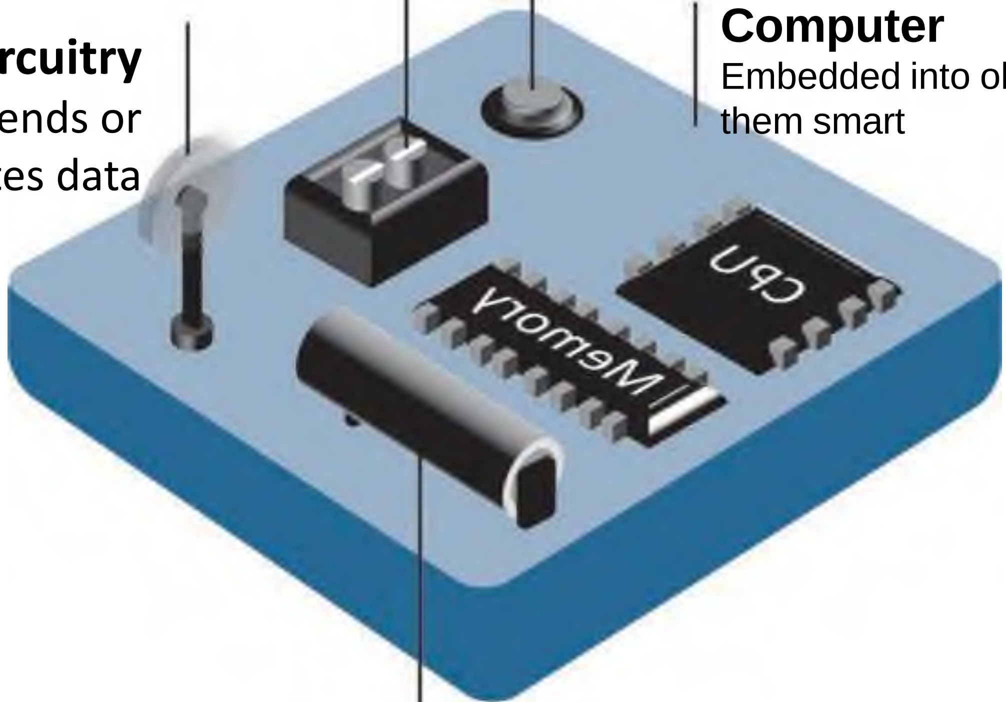
Πανεπιστήμιο Κύπρου

Sensor
Measure physical data
(temperature, vibration, pollution…)

Actuator
Capable of performing a task
(change traffic lights)

Communication Circuitry
Receives instructions, sends or
routes data

Computer
Embedded into objects to make
them smart



Power Source
Scavenger (solar/wind), battery, mains

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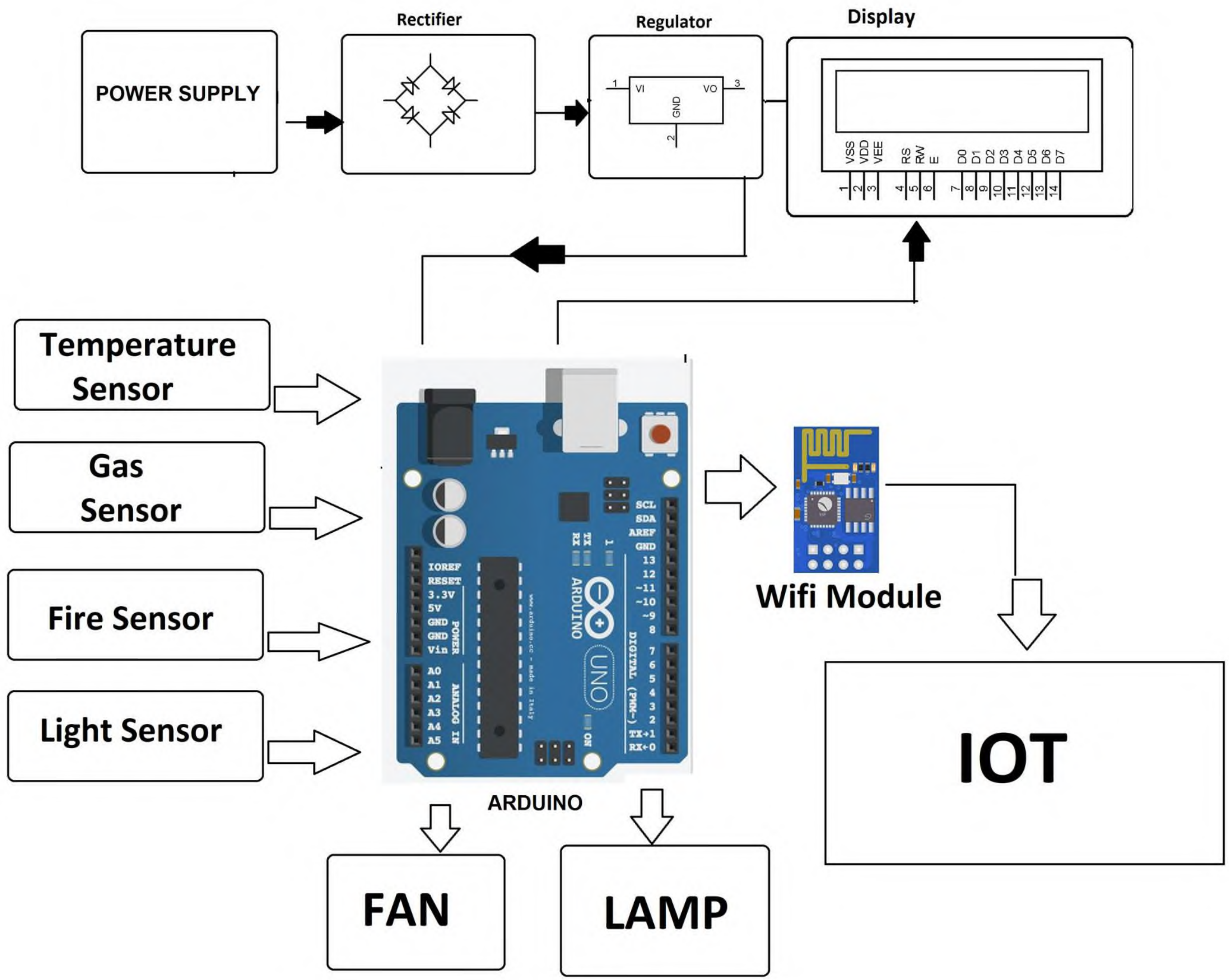
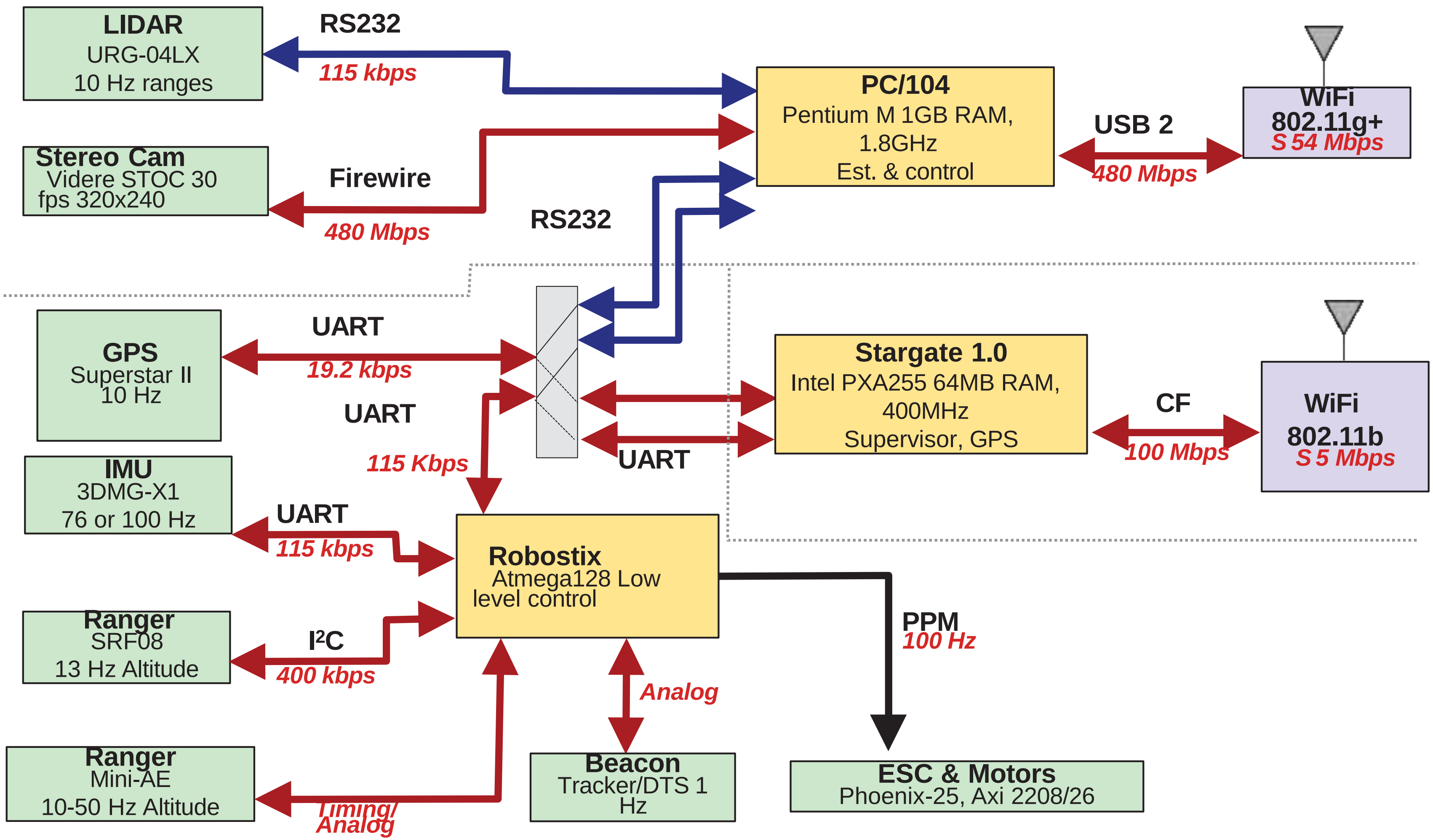
HIGH-LEVEL DEVICE ARCHITECTURE



LOW-LEVEL DEVICE ARCHITECTURE



Πανεπιστήμιο Κύπρου

- IoT applications summon a large volume of data generated from a large number of devices
- Data is generated using sensors, embedded devices and systems
- Thereafter, the data is communicated through the data-link, data- adaptation, network, application-support and application layers to the applications of IoT
- Data is used for analytics, visualisation, intelligence and knowledge discovery or controls and monitoring. Control systems use the **sensors** for monitoring and the **actuators** for control of the environment

Πανεπιστήμιο Κύπρου

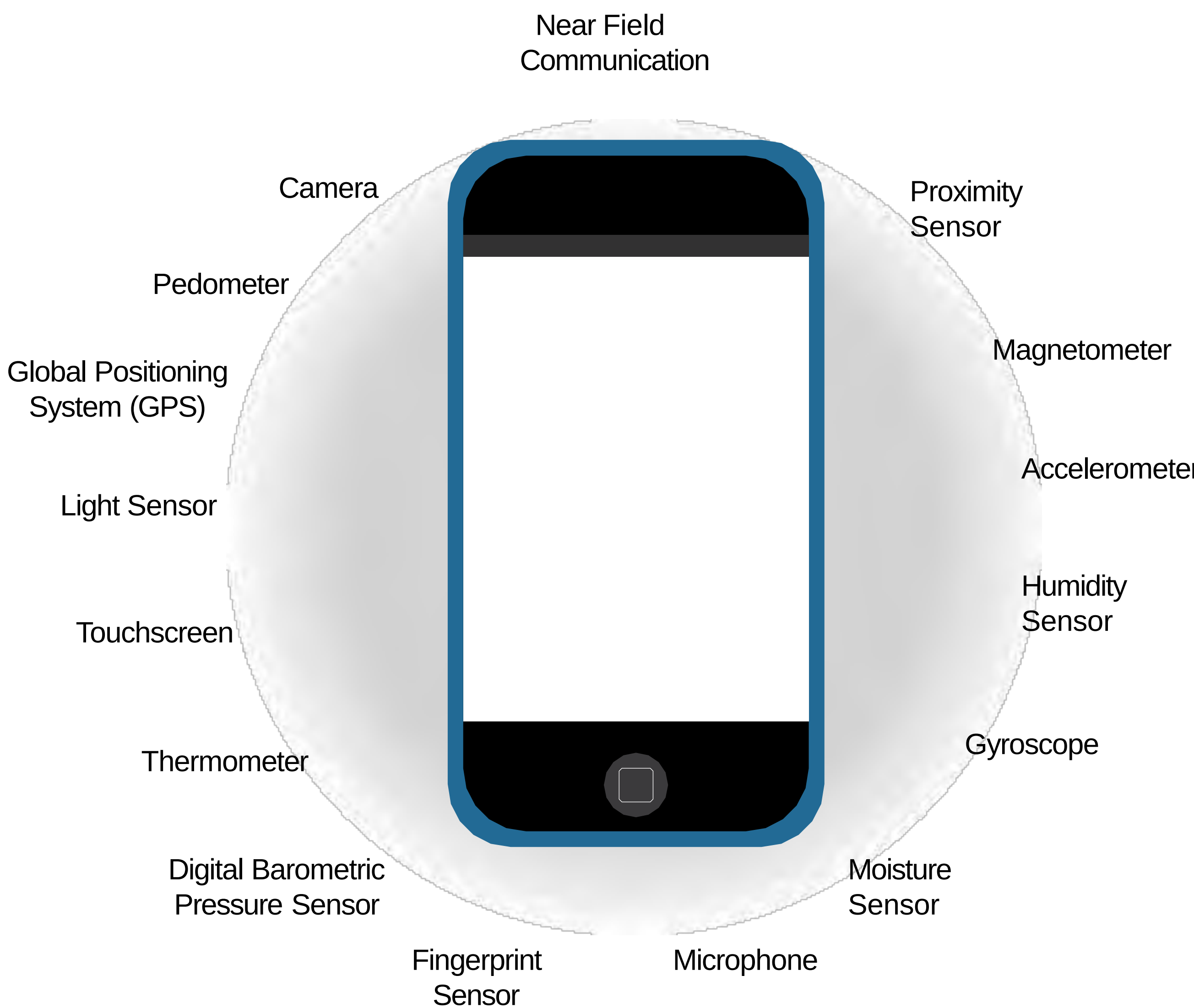
- Sensor technology is used for designing sensors and associated electronic readers, circuits and devices
- Can sense a change in physical parameters, such as temperature, pressure, light, smoke and proximity to an object.
- Sensors can also sense acceleration, orientation, location, vibrations or smell, etc
- A microphone senses air vibrations and is used to record voice or music
- A sensor converts physical energy like heat, sound, strain, pressure, vibrations and motion into electrical energy
- A **smart sensor** includes the **electronic circuit** within itself, and **computing** and **communication** capabilities

- Myriad different sensors to measure the physical world
- **Active or passive**: Require an external power supply (active) or whether they simply receive energy
- **Invasive or non-invasive**: Part of the environment it is measuring (invasive) or external to it (non-invasive)
- **Contact or no-contact**: Require physical contact with what they are measuring (contact) or not (no-contact)
- **Absolute or relative**: In absolute scale (absolute) or based on a difference with a fixed or variable reference value (relative)
- **How sensors measure**: Physical mechanism used to measure sensory input (for example, thermoelectric, electrochemical, piezoresistive, optic, electric, fluid mechanic, photoelastic)
- **What sensors measure**: what physical variables they measure

Πανεπιστήμιο Κύπρου

Sensor Types	Description	Examples
Position	Position can be either in absolute or relative terms (displacement sensor). Position sensors can be linear, angular, or multi-axis	Potentiometer, inclinometer, proximity
Occupancy and motion	Detect the presence of objects while motion sensors detect movement. Occupancy sensors generate a signal even when a person is stationary	Radar
Velocity and acceleration	Speed of motion may be linear or angular, indicating straight or rotating speed. Acceleration sensors measure changes in velocity	Accelerometer, Gyroscope
Force	Detect whether a physical force is applied and whether the magnitude of force is beyond a threshold.	Force gauge, viscometer, touch/ tactile
Pressure	Measuring force applied by liquids or gases. Pressure is measured in terms of force per unit area.	Barometer, Bourdon gauge, piezometer
Flow	Detect the rate of fluid flow. Measure the volume (mass flow) or rate (flow velocity) of fluid that has passed through a system in a given period of time.	Anemometer, mass flow sensor, water meter
Acoustic	Measure sound levels and convert that information into digital or analog data signals	Microphone, geophone, Hydrophone
Humidity	Detect humidity (amount of water vapor) in the air or a mass. Humidity levels can be measured in various ways: absolute humidity, relative humidity, mass ratio, and so on.	Hygrometer, humistor, soil moisture sensor
Light	Light sensors detect the presence of light (visible or invisible).	Infrared sensor, photodetector
Radiation	Detect radiation in the environment. Radiation can be sensed by scintillating or ionization detection	Geiger-Müller counter, neutron detector
Temperature	Measure the amount of heat or cold, two types: contact and non-contact. Non-contact measure temp. through convection and radiation	Thermometer, Calorimeter
Biosensors	Biosensors detect various biological elements, such as organisms, tissues, cells, enzymes, antibodies, and nucleic acid	Pulse oximetry, EEG, ECG, etc

Πανεπιστήμιο Κύπρου



Πανεπιστήμιο Κύπρου

- Electrical energy conveys information in variations through currents, voltages, phase- angles or frequencies
- Analog sensors generate analog outputs and thus Analog-to-Digital Converter (**ADC**) is employed in digital systems
- A sensor packaged with an ADC is called a **digital sensor**
- Digital sensor will have a limited precision, determined by the number of bits used to represent the number during the ADC
- An actuator is commonly driven by a voltage that may be converted from a number by a digital-to- analog converter (**DAC**)
- An actuator that is packaged with a DAC is called a **digital actuator**

- Key properties of sensors include the rate at which measurements are taken or actuations are performed
- Proportionality constant that relates the physical quantity to the measurement or control signal
- The offset or bias, and the dynamic range
- For many sensors and actuators, it is useful to model the degree to which a sensor or actuator deviates from a proportional measurement (its nonlinearity), and the amount of random variation introduced by the measurement process (i.e. noise)
- Measurements of physical phenomena must be **quantized** in both magnitude and time for digital systems to process

- Sensors may be approximately modeled by an affine function
- Physical quantity x(t) at time t is reported by the sensor to have value f (x(t)),
- Function **f** is linear if there exists a proportionality constant a ∈ R such that for all x(t) ∈ R

$$f(x(t)) = ax(t)$$

- It is an **affine function** if there exists a proportionality constant a ∈ R and a bias b ∈ R

$$f(x(t)) = ax(t) + b$$

- Proportionality constant represents the **sensitivity** of the sensor

Πανεπιστήμιο Κύπρου

- the **range** of a sensor is the set of values of a physical quantity that it can measure, is always limited
- Outside that range, an affine function model is no longer valid
- For example, a thermometer designed for weather monitoring may have a range of -20° to 50° Celsius
- Physical quantities outside this range will typically **saturate**, meaning that they yield a maximum or a minimum reading outside their range, i.e.:

$$f(x(t)) = \begin{cases} ax(t) + b & \text{if } L \leq x(t) \leq H \\ aH + b & \text{if } x(t) > H \\ aL + b & \text{if } x(t) < L, \end{cases}$$

Πανεπιστήμιο Κύπρου

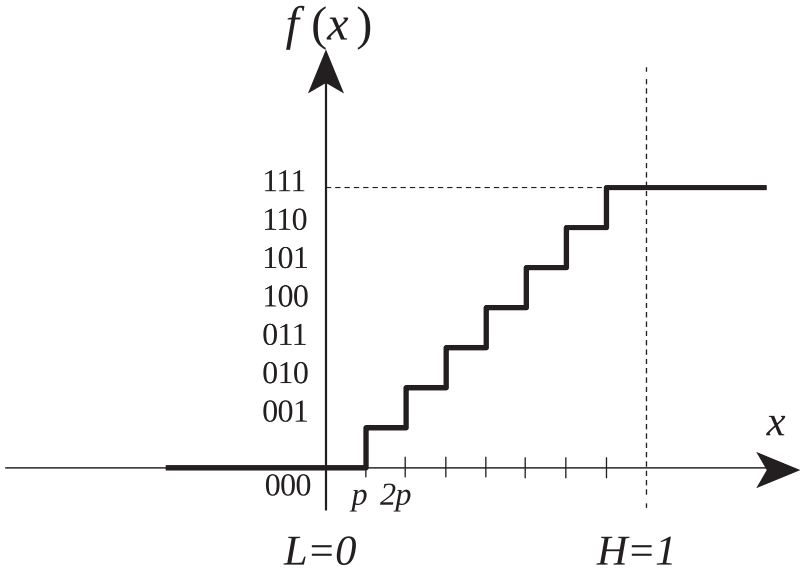
- Digital sensors are unable to distinguish between two closely-spaced values of the physical quantity
- **Precision p** of a sensor is the smallest absolute difference between two values of a physical quantity whose sensor readings are distinguishable
- The dynamic range D ∈ R+ of a digital sensor is the ratio

$$\mathrm{D} = \frac{H - L}{p}$$

- Dynamic range is usually measured in decibels:

$$D_{dB} = 20 \log_{10} \frac{H - L}{p}$$

- A digital sensor represents a physical quantity using an n-bit number, i.e. **quantization**
- 2^n distinct such numbers are available to represent measurements and thus $p = (H - L)/2^n$
- A real number value $x(t) \in R$ must be mapped to one of the 2^n numbers
- Two physical quantities that differ by the precision p will be represented by digital quantities that differ by one bit



- 3-bit digital sensor,
- Values between L=0 / H = 1
- $p = 1/8$

$$D_{dB} = 20 \log_{10} \frac{H-L}{p} \approx 18dB$$

Πανεπιστήμιο Κύπρου

EXAMPLE

- An extreme form of quantization is performed by an analog comparator
- Compares a signal value against a threshold
- Produces a binary value
- Sensor function f : R → {0, 1} :

$$f(x(t)) = \begin{cases} 0 & \text{if } x(t) \leq 0 \\ 1 & \text{otherwise} \end{cases}$$

- Such extreme quantization is often useful, because the resulting signal is a very simple digital signal that can be connected directly to a GPIO input pin of a microprocessor
- Analog comparator is a one-bit ADC

Πανεπιστήμιο Κύπρου

- Quantization error for 1-bit ADC **but** using signal conditioning, with high sample rate, the approximation noise can be reduced considerably by digital low-pass filtering
- Such a process is called **oversampling**; it is commonly used because processing signals digitally is often less costly than analog processing
- **Trade off precision (bits) and speed (sampling time)**
- Same applies to actuators
  - Precision with which an analog action can be taken depends on the number of bits of the digital signal and the range of the actuator
  - But one-bit digital actuation signal updating frequently a slow-response actuator (e.g. motor) applies small gradual reactions and thus smoother result

- noise is the part of a signal that we do not want
- If we want to measure x(t) at time t, but we actually measure xl(t)), then the noise is the difference

$$n(t) = x^{l}(t) - x(t)$$

- Equivalently, the actual measurement is

$$x^{l}(t) = x(t) + n(t)$$

- We can also model sensor **imperfections** and **quantization** as noise
- In general, a sensor distortion function can be modeled as additive noise

$$f(x(t)) = x(t) + n(t)$$

Πανεπιστήμιο Κύπρου

- To characterize how much noise there is in a measurement
  - Root mean square (RMS) N ∈ R+

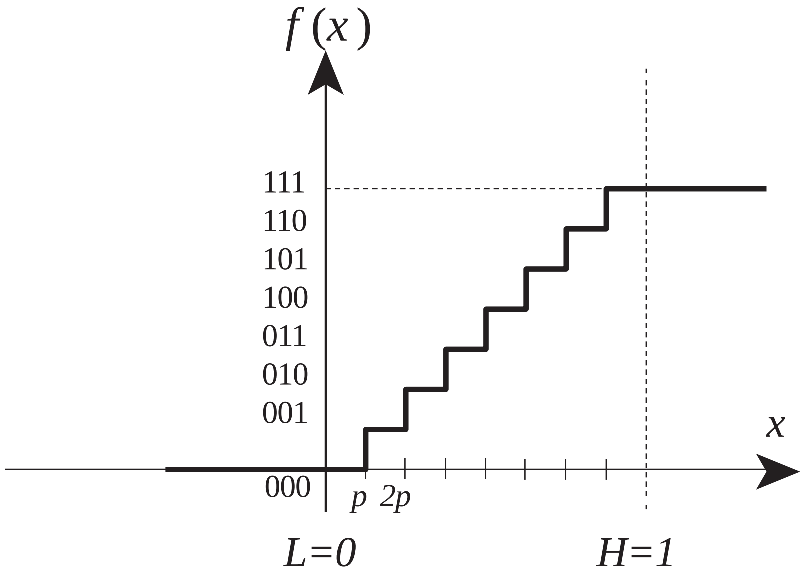
$$N = \lim_{T\to\infty} \sqrt{\frac{1}{2T}\int_{-T}^{T}(n(\tau))^2 d\tau}$$

- Signal to noise ratio (**SNR**), in decibels, is defined in terms of RMS noise

$$SNR_{dB} = 20\log_{10}\frac{X}{N}$$

- where X is the RMS value of the input signal x

EXAMPLE CONTINUED



- 3-bit digital sensor,
- Values between L=0 / H = 1 Volt
- $p = 1/8$

- Assuming equal likely values (uniform distribution)

$$X = \sqrt{\int_0^1 x^2 dx} = \frac{1}{\sqrt{3}}$$

$$N = \sqrt{\int_{-1/8}^{0} 8n^2 dn} = \frac{1}{8\sqrt{3}}$$

$$SNR_{dB} = 20\log_{10}\frac{X}{N}$$
$$= 20\log_{10}(8) \approx 18dB$$

Πανεπιστήμιο Κύπρου

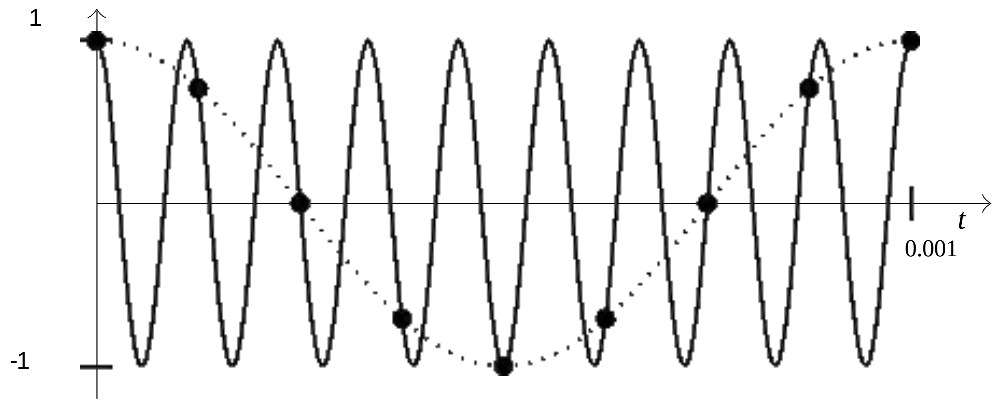
- A physical quantity x(t) is a function of time t
- A digital sensor will sample the physical quantity at particular points in time to create a discrete signal.
- In uniform sampling, there is a fixed time interval T between samples;
  - T is called the sampling interval.
- The resulting signal may be modeled as a function

$$s(n) = f(x(nT)) \ \forall n \in Z$$

with sampling rate is 1/T Hertz (written Hz, meaning cycles per second).

Πανεπιστήμιο Κύπρου

- Importantly when sampling signals there may be many distinct functions x will yield the same output
- This phenomenon is known as **aliasing**



- Nyquist Sampling Theorem
  - A sample rate R = 2/T (i.e. twice the sampling frequency) uniquely defines a continuous-time signal

Πανεπιστήμιο Κύπρου

- A form of **nonlinearity** in the signal is harmonic distortion
- Occurs when the sensitivity of the sensor or actuator is not constant and depends on the magnitude of the signal
- For example, a microphone may be less responsive to high sound pressure than to lower sound pressure

$$f(x(t)) = ax(t) + b + d_2 (x(t))^2$$

- Example
  - microphone receives sound

$$x(t) = \cos(\omega_0 t)$$

where t is time in seconds and ω0 is the frequency of the sinusoid in radians per second

$$x^{l}(t) = ax(t) + b + d_2 (x(t))^2$$
$$= a\cos(\omega_0 t) + b + d_2 \cos^2(\omega_0 t)$$

Πανεπιστήμιο Κύπρου

- Noise and harmonic distortion often have significant differences from the desired signal
- We can exploit those differences to reduce or even eliminate the noise or distortion.
- Use frequency selective filtering based on Fourier theory
    - A signal is an additive composition of sinusoidal signals of different frequencies
- Need to have a model of both the desired signal x and the noise n
- Reasonable models are usually statistical, and analysis of the signals requires using the techniques of random processes, estimation, and machine learning
- Example:
    - Signal xl = x + n filtered by a LTI system S
    - Let the output of the conditioning filter be given by

$$y = S(xl) = S(x + n) = S(x) + S(n)$$

- Let the residual error signal after filtering be defined to be

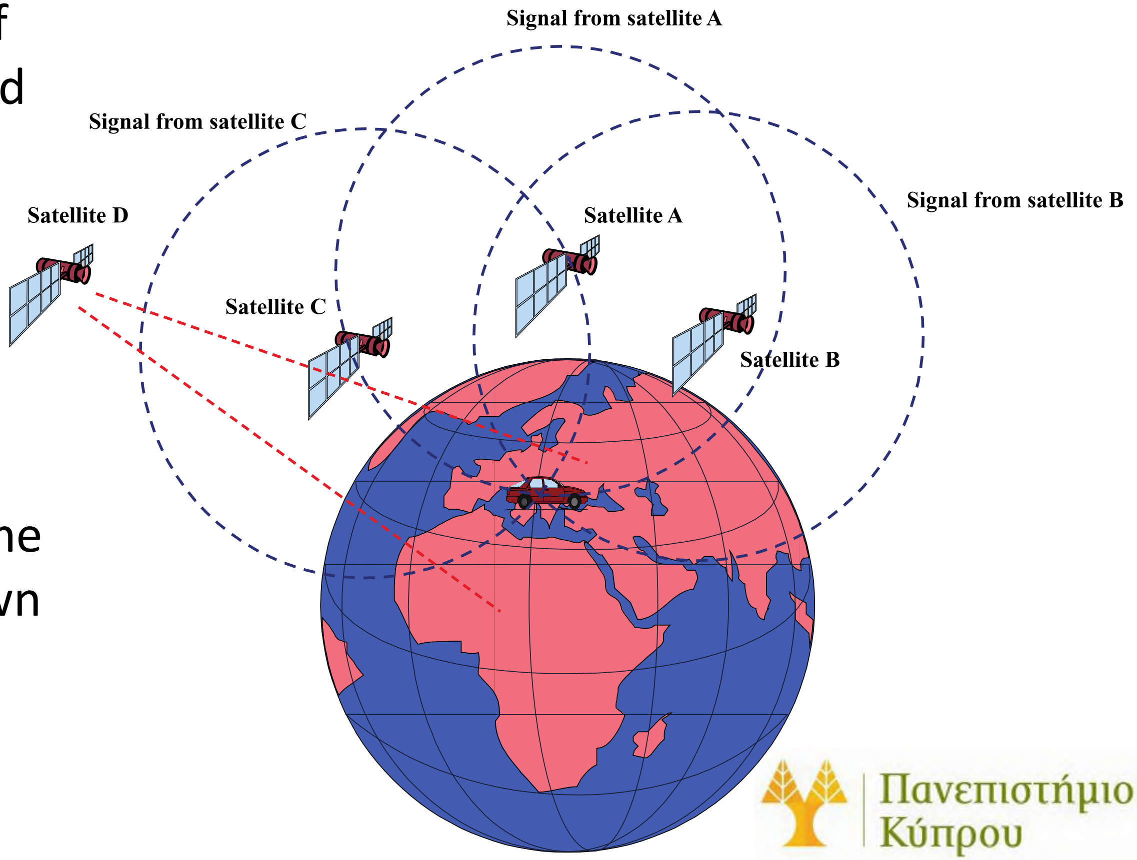
$$r = y - x = S(x) + S(n) - x$$

- Let R denote the RMS value of r, and X the RMS value of x

$$SNR_{dB} = 20 \log_{10} \frac{X}{R}$$

COMMON SENSORS

- Direct measurements of position using satellite signal triangulation
- >4 GPS satellites that carry extremely precise clocks
  - transmit time of transmission and the location of the satellite at the time of transmission
  - receiver calculates distance and time offset to find own position



Πανεπιστήμιο Κύπρου

- GPS satellites is relatively weak and is easily blocked by buildings and other obstacles
- Indoor localization uses mechanisms
    - WiFi fingerprinting where a device uses the known location of WiFi access points, the signal strength from those access points, to estimate the location
    - Bluetooth beacons used with signal strength giving a rough indication of distance and thus location
    - However in both cases signal strength is a poor measurement of distance due to multipath (constructive and destructive interference)

- Gyroscopes measure changes in orientation (rotation)
    - based on MEMS devices (microelectromechanical systems) using small resonating structures, or optical devices that measure the difference in distance traveled by a laser beam
- Gyroscopes and accelerometers may be combined to improve the accuracy of inertial navigation
    - position estimated using dead reckoning.
    - starting from a known initial position and orientation,
    - measurements of motion used to estimate subsequent position and orientation
- Inertial measurement unit (IMU)
    - uses a gyroscope to measure changes in orientation and an accelerometer to measure changes in velocity

ACTUATORS

Πανεπιστήμιο Κύπρου

- Actuators receive a control signal (commonly an electric signal or digital command) that triggers a physical effect, usually some type of motion, force, etc
- Actuators vary greatly in function, size, design:
    - Type of motion: Classified based on the type of motion produced (linear, rotary, one/two/three-axes)
    - Power level: Output (high power, low power, micro power)
    - Binary or continuous: Number of stable-state outputs
    - Type of energy expended (mechanical, electrical, electromagnetic, hydraulic, etc)

- Very few actuators can be driven directly from the digital I/O pins
  - Can source or sink a limited amount of current, and any attempt to exceed this amount risks damaging the circuits.
  - One exception is light-emitting diodes (LEDs)
- Better alternatively is to switch on or off using a digital signal from a microcontroller
- Pulse width modulation (PWM)
  - Switches between a high level and a low level at a specified frequency
  - Holds the signal high for a fraction of the duty cycle

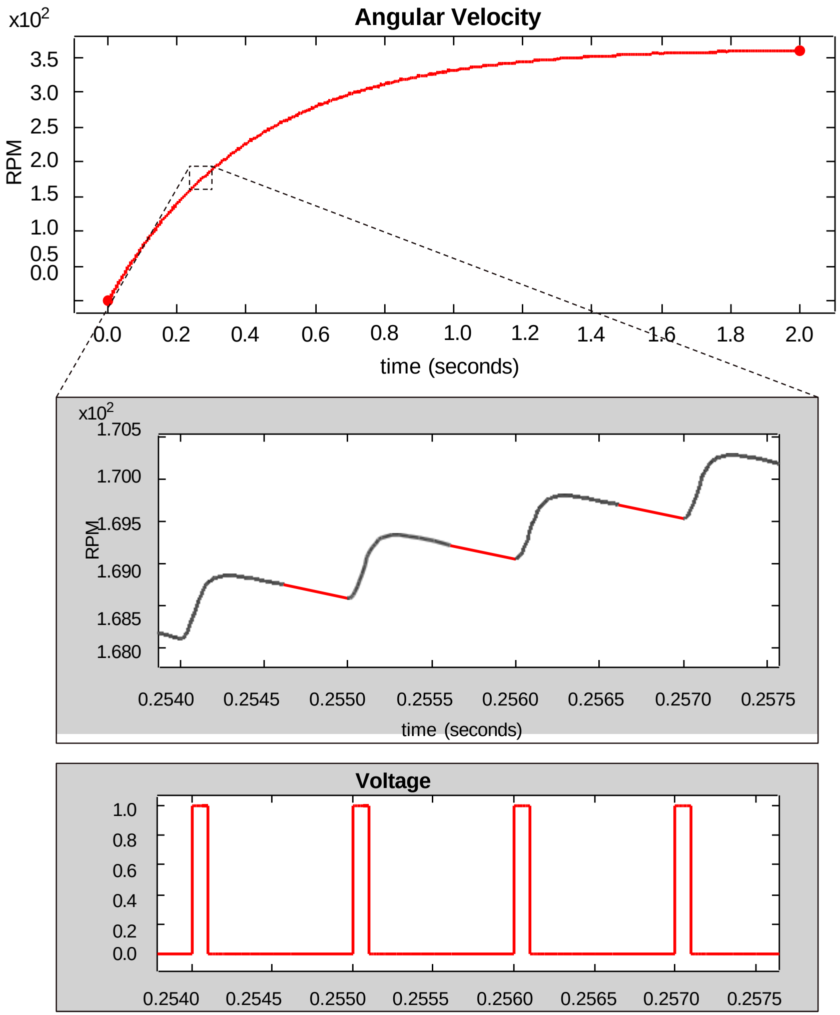
- A motor applies a torque (angular force) to a load proportional to the current through the motor windings
- DC motor consists of an electromagnet made by winding wires around a core placed in a magnetic field made with permanent magnets or electromagnets
- When current flows through the wires, the core spins
  - has both inertia and inductance that smooth its response when the current is abruptly turned on and off
  - Let ω be the angular velocity when voltage v is applied

$$v(t) = Ri(t) + L\frac{di(t)}{dt} + k_b\omega(t)$$

  - k_b is an empirical **back electromagnetic force constant**
  - R is the resistance and L the inductance

- Consider a particular motor with the following parameters

I	3.88 x 10^{-7} kg m2
kb	2.75 x 10^{-4} volts/RPM
kT	5.9 x 10^{-3} newton meter/amp
R	1.71 ohms
L	1.1 x 10-4 henrys
f	1kHz
duty cycle	0.1



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