Overview

- Interfacing with the Physical Environment
- Signals, Discretisation
- Input (Sensors)
- Output (Actuators)
- Analog/Digital Conversion, Digital/Analog Conversion
Interfacing with the Physical Environment

CPS & ES hardware is frequently used in a loop ("hardware in a loop"): 

A/D converter
sample-and-hold

information processing

display

D/A converter

actuators

sensors

(physical) environment

Cyber-physical systems (!)
Sensors

- Capture physical/chemical quantity and convert to electrical quantity

- Sensors for many physical and chemical quantities, including
  - weight, velocity, acceleration, electrical current, voltage, temperatures, and
  - chemical compounds.

- Many physical effects used for constructing sensors.
  - law of induction (generation of voltages in a magnetic field),
  - light-electric effects.
Sensors - Examples

- Acceleration Sensor
- Temperature Sensor, Pressure Sensor
- Image Sensor
- Rain sensors for wiper control, Proximity sensors, Engine control sensors ("Sensors multiply like rabbits" [ITT automotive])
- Hall effect sensors, ...
- Deliver electrical representation of original physical/chemical quantity
Signals

Sensors generate *signals*

**Definition:** A signal $s$ is a mapping from the time domain $D_T$ to a value domain $D_V$:

$$s : D_T \rightarrow D_V$$

$D_T$: continuous or discrete time domain

$D_V$: continuous or discrete value domain.
Discretisation of Time

Digital computers require discrete sequences of physical values

$s : D_T \rightarrow D_V$

Discrete time domain

Sample-and-hold circuits
Sample and Hold

Clocked transistor + capacitor;
Capacitor stores sequence values

$e(t)$ is a mapping $\mathbb{R} \rightarrow \mathbb{R}$

$h(t)$ is a sequence of values or a mapping $\mathbb{Z} \rightarrow \mathbb{R}$
Aliasing

Periods of $p=8,4,1$
Indistinguishable if sampled at integer times, $p_s=1$
Sampling Theorem

Reconstruction impossible, if not sampling frequently enough

How frequently do we have to sample?

**Nyquist criterion** (sampling theory):

Aliasing can be avoided if we restrict the frequencies of the incoming signal to less than half of the sampling rate.

\[ p_s < \frac{1}{2} p_N \] where \( p_N \) is the period of the “fastest” sine wave

or \( f_s > 2 f_N \) where \( f_N \) is the frequency of the “fastest” sine wave

\( f_N \) is called the **Nyquist frequency**, \( f_s \) is the **sampling rate**.
Anti-Aliasing Filter

A filter is needed to remove high frequencies

e(t) \quad \text{anti-aliasing} \quad g(t) \quad \text{Sample- & hold} \quad h(t)

\frac{g(t)}{e(t)}

\text{Ideal filter}

\text{Realizable filter} \quad \frac{f_s}{2} \quad f_s

e_4(t) \text{ changed into } e_3(t)
Discretisation of Values

Digital computers require digital form of physical values

\[ s: D_T \rightarrow D_V \]

\[^\text{A/D-conversion; many methods with different speeds.}\]
Flash A/D Converter

No decoding of $h(t) > V_{ref}$

Encoding of voltage intervals

$h(t)$

$V_{ref}$

$\frac{3}{4}V_{ref}$

$\frac{2}{4}V_{ref}$

$\frac{1}{4}V_{ref}$

Comparators

Encoding

Digital outputs $w(t)$
Resolution

- Resolution (in bits): number of bits produced
- Resolution $Q$ (in volts): difference between two input voltages causing the output to be incremented by 1

\[ Q = \frac{V_{ref}}{4} \] for the previous slide

\[ Q: \] resolution in volts per step
\[ V_{FSR}: \] difference between largest and smallest voltage
\[ n: \] number of voltage intervals

Example:
\[ Q = \frac{V_{ref}}{4} \] for the previous slide
Quantisation Noise

Assuming "rounding" (truncating) towards 0
Signal to Noise Ratio

\[
\text{signal to noise ratio (SNR)} [\text{dB}] = 20 \log_{10}\left(\frac{\text{effective signal voltage}}{\text{effective noise voltage}}\right)
\]

e.g.: \(20 \log_{10}(2)=6.02 \text{ decibels}\)

Signal to noise for ideal \(n\)-bit converter: \(n \times 6.02 + 1.76 [\text{dB}]\)
e.g. 98.1 dB for 16-bit converter, ~ 160 dB for 24-bit converter

Additional noise for non-ideal converters
Actuators

• Huge variety of actuators and output devices.

• Indicator lights (LED), LCD screen, ...

• Relais, Optocouplers, ...

• Motor, motorised valves, heaters, ...

• Speakers, Buzzers, ...

• Analog output: Digital-Analog-Converters
Digital/Analog Conversion

Various types, can be quite simple, or more advanced.
Digital/Analog Conversion

Loop rule:

\[ x_0 \times I_0 \times 8 \times R + V_- - V_{ref} = 0 \]

\[ I_0 = x_0 \times \frac{V_{ref}}{8 \times R} \]

In general:

\[ I_i = x_i \times \frac{V_{ref}}{2^{3-i} \times R} \]

Junction rule:

\[ I = \sum_i I_i \]

\[ I = x_3 \times \frac{V_{ref}}{R} + x_2 \times \frac{V_{ref}}{2 \times R} + x_1 \times \frac{V_{ref}}{4 \times R} + x_0 \times \frac{V_{ref}}{8 \times R} = \frac{V_{ref}}{8 \times R} \times \sum_{i=0}^{3} x_i \times 2^i \]

\[ I \sim nat(x), \text{ where } nat(x): \text{natural number represented by } x; \]

Hence:

\[ y = -V_{ref} \times \frac{R_1}{8 \times R} \sum_{i=0}^{3} x_i \times 2^i = -V_{ref} \times \frac{R_1}{8 \times R} \times nat(x) \]

Op-amp turns current \( I \sim nat(x) \) into a voltage \( y \sim nat(x) \)
Processing Chain

* Assuming “zero-order hold”

Possible to reconstruct input signal?
Pulse Width Modulation

• Commonly used technique for controlling power to inertial electrical devices

• Average value of voltage (and current) fed to the load is controlled by turning the switch between supply and load on and off at a fast pace
  
  • The longer the switch is on compared to the off periods, the higher the power supplied to the load is

• Made practical by modern electronic power switches

• Greater efficiency
  
  • Switching - nearly lossless
  
  • Linear - “burn” excess voltage in resistor
Pulse Width Modulation
Summary

• Embedded System operates in physical environment: interfacing

• Discretisation: Time/Values

• Sensors: A/D Conversion

• Actuators: D/A Conversion, PWM
Preview

• Models of Computation