Sensors and Actuators

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Introduction

- Sensors can measure physical quantities
- Actuators alters physical quantities
- Digital sensor - sensors packaged with analog-to-digital converter (ADC)
- Analog sensor - without ADC
- Digital actuator - actuator packaged with DAC
- IoT

Modeling of sensors & actuators

- Rate at which measurements are read and rate at which actuations are performed
- Proportionality constant
- How the read value is related to actual quantity
- Offset, bias, range
- Non-linearity, noise, sampling
- Analog, digital, quantization
- Sensing issue - tilt, measuring position, velocity
- Security, privacy, commissioning, network interface

Linear and affine

- Let us assume physical quantity be $x(t)$ and the reported be $f(x(t))$
- The reported one will be linear if $f(x(t)) = ax(t)$ and a is constant
- Affine function if $f(x(t)) = ax(t) + b$ holds where a, b are constants
- Proportionality constant represents sensitivity

Range

- No sensor is truly linear
- It saturates outside of operating zone

$$f(x(t)) = \begin{cases} ax(t) + b & L \leq x(t) \leq H \\ c_1 & x(t) > H \\ c_2 & x(t) < L \end{cases}$$

- Non-linear but piecewise affine

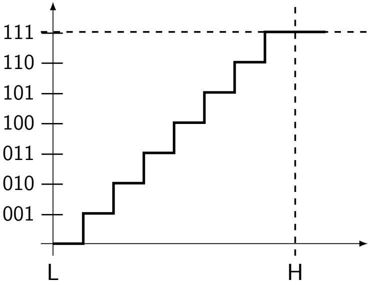
Dynamic range

- Digital sensors are unable to distinguish between two closely spaced values
- Precision - smallest absolute difference between two values which is distinguishable
- If the range of a sensor is $H - L$ and there are p levels, then the dynamic range is measured as $D = \frac{H-L}{p}$
- Often this is measured in decibel

$$D_{dB} = 20 \log_{10} \left(\frac{H-L}{p} \right)$$

Quantization

- Digital sensors represent physical quantity using n bit number, so there will be 2^n distinct such numbers
- Precision and quantization are related to each other
- Extreme quantization — 0/1



Noise

- Unwanted signal
- If we want to measure $x(t)$ and actually measure $x'(t)$, the the noise will be $n(t) = x'(t) - x(t)$
- Example: measuring orientation of an slowly moving object
- Measured as root mean square, that is $n = \lim_{t \to \infty} \sqrt{\frac{1}{2T} \int_0^T (n(\tau))^2 d\tau}$
  - It measures noise power
- Signal-to-noise ratio $SNR_{dB} = 20 \log_{10}(\frac{X}{N})$
- Consider a 3-bit digital sensor with operating range of zero to one volt. Assume that the input voltage is equally likely to be anywhere in the range of zero to one volt. What is the RMS value of input signal? What is RMS error at the output?

Sampling

- A digital sensor will sample the physical quantity at a particular point of time to create discrete signal
- Uniform sampling - fixed time interval (T) between samples. T is called sampling interval
- Resulting signal may be modeled as $s : Z \to R$ $s(n) = f(x(nT))$
- Sampling rate is $1/T$ that is samples per second
- Aliasing

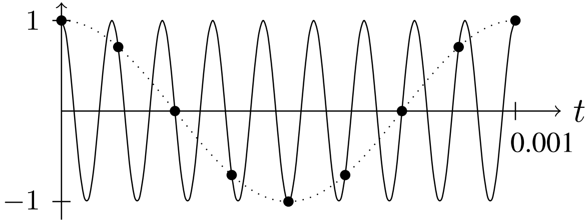


image source: Introduction to Embedded Systems book

Harmonic distortion

- Non-linearity occurs due to harmonic distortion
- Second harmonic distortion - $f(x(t)) = ax(t) + b + d_2(x(t))^2$
- Suppose a microphone is given pure sinusoid wave $x(t) = \cos(\omega_0 t)$
- Sensor output will be

$$\begin{aligned} x'(t) &= ax(t) + b + d_2(x(t))^2 = a\cos(\omega_0 t) + b + d_2\cos^2(\omega_0 t) \\ &= a\cos(\omega_0 t) + b + \frac{d_2}{2} + \frac{d_2}{2}\cos(2\omega_0 t) \end{aligned}$$

Common sensors

- Magnetometers
- Cameras
- Accelerometers
- Rate gyros
- Strain gauges
- Microphone
- Radar
- Chemical sensors
- Pressure sensors
- and many more

Actuators

- Light emitting diodes
- Motor controllers
- Solenoids
- LCD, plasma display
- Loud speakers