11. Practical Considerations

transducers (sensors & actuators) :

↕ incompatibility

measurement and control systems : suited to handle information.

digitization of analog signals (§11.1)

signal conditioning (§11.2)

issues arising from digitization

novel sensing mechanisms (§11.3)

arrays and large elements (§11.4)

11.1 Digitization of Analog Signals

transduction mechanisms are fundamentally in nature

→ incompatibility between analog and digital information

at the interface between a transducer and a computer (processing hardware)

ex.

converting an analog signal into a digital signal for an electromechanical transducer

1. electrical digitization

   digital hardware in the form of an

2. mechanical digitization

   transducer itself so that the electrical signal produced (or accepted) is in digital form

1. electrical conversion

Fig. 11.1

electromechanical transducers with a digital processing scheme

sensor -(A)→ amplifier -(A)→ filter -(A)→ *A to D conversion* -(D)

↓

actuator ←(A)- filter ←(A)- *D to A conversion* ←(D)- digital processing

<analog-to-digital signal converters>

sample and hold circuit

tracks an analog input for a short period of time, and then
holds the last value tracked for the remainder of the duty cycle

comparator

compares two input signals and decides which is larger

encoding circuit

permits the output signals of the comparators to be converted
to the appropriate ones and zeros of a digital sequence

ex. Fig. 11.2 a parallel converter (a

<digital-to-analog signal converters>

no need for a sample and hold circuit nor for a comparator

usually build from resistive networks

requires an   to sum the currents received from the networks

ex. Fig. 11.3

2. mechanical digitization

add a mechanical modulator to an analog transducer

to discretize an otherwise continuously variable signal

Ex.1

Fig. 11.4 optical encoder disk separating light source from a set of photodiodes

Fig. 11.5 a three-bit binary optical encoder disk

Ex.2

a vibrating sensor consisting of a series of vibrating reeds, each a cantilever beam with metal deposited onto it

as the sensor is subjected to vibration excitation, each reed vibrates

a voltage is applied between the tip of each beam and a pad at a fixed distance

by way of digitization of the sensor

if the reed vibrates enough to touch the pad (close to the switch), current flows

otherwise no current flows

by varying the size or material of the reeds, the reeds have different thresholds for switching from high- to low-current flow

11.2 Signal Conditioning

amplifier and filters in Fig. 11.1

necessary as a result of the conversion of analog to digital signals

and

filters

necessary as a result of the signal at discrete times

amplifiers at the input stage

needed in order to achieve the maximum

11.2.1 filtering

<u>sampling</u>

represent a continuous signal $s(t)$ by a set of discrete values at intervals of τ

⇒ values of s at times $0,\ \tau,\ 2\tau,\ \cdots,\ (N-1)\tau$

i.e. $s_n = s(n\tau) \qquad n = 0,\ 1,\ \cdots,\ N-1$

time domain is effectively discretized ⇒ frequency domain is

Fourier transform

$$S_k = \frac{1}{N}\sum_{n=0}^{N-1} s_n\ e^{-j2\pi kn/N} = \frac{1}{N}\sum_{n=0}^{N-1} s_n\ e^{-j(2\pi k/N\tau)(n\tau)} \qquad (1)$$

$n\tau$:

summation = discrete version of integration over time

$2\pi k/N\tau$:

$$\omega = 0,\ \frac{2\pi}{N\tau},\ \frac{4\pi}{N\tau},\ \cdots,\ \frac{2(N-1)\pi}{N\tau} \approx \frac{2\pi}{\tau}$$

discrete frequencies are spaced uniformly ← time signals are uniformly spaced

the highest frequency ←

<u>effect of sampling</u>

Fig. 11.6 (a) a continuous sinusoidal signal

(b) a discrete representation by sampling

the discrete signal is a good approximation to the continuous one

Fig. 11.7 (a) a high-frequency continuous signal

(b) a discrete representation using a too low sampling

the discrete signal does not resemble the continuous one

clear problem if the discrete samples are spaced too far apart in time

⇒ must sample faster than half the period of a sinusoidal signal

in order to see all of the zero crossings clearly

Nyquist frequency F_{Ny} =

aliasing problem

distortion of a signal due to a   sampling rate

if a continuous signal contains frequencies higher than f_{Ny},

then those frequency components are mapped erroneously into   frequencies

ex. Fig. 11.7   (a) a continuous signal -(mapped)→ (b) a signal at zero frequency

avoid aliasing only by removing the   frequency components from the signal before sampling

⇒   filtering before ADC

ADC with high (fast) sampling rate is desirable

windowing problem

distortion of a signal in the frequency domain due to finite duration in time domain

ex. Fig. 11.8 (a) an arbitrary signal of finite duration

(b) the continuous time signal which the FFT process imagines

repetition of the signal over and over again

⇒ erroneous high-frequency content

prevent repetition of the sampled signal

by changing the rectangular window into

- a one-half period of squared cosine function
- Hanning window
- Hamming window
- Tchebyshev window

⇒   the signal in the time domain

in order to produce   distortion of the frequency domain representation

filtering hardware specifications

bandwidth

a measure of what frequencies are passed essentially unscathed

in most filters, the bandwidth is adjustable

skirt slope

a measure of how much attenuation of signals outside the bandwidth is available

ex. a low-pass filter skirts of -40 dB/decade

= at the frequency 10 times above the knee in the filter, the signal is attenuated by 40 dB

ripple

a measure of smoothness in the bandpass region of the filter

the less ripple, the better the filter in general

11.2.2 amplifying

a signal is discretized in amplitude as well as in time during the AD conversion

⇒ need for amplification of analog signals before

<u>quantization error</u>

unavoidable noise introduced in the process discretizing the amplitude of an analog signal

each bit of a digital representation :

if $0 \le S \le \frac{1}{2}$, then $S \rightarrow$

otherwise $S \rightarrow$

the largest possible error is

for m bit representation, the maximum error is

signal-to-noise ratio

for a single bit converter	$\frac{1}{1/2} = 2$	$20 \log 2 =$
" two bit "	$\frac{1}{1/2^2} = 2^2$	$20 \log 2^2 =$
" 12 bit "	$\frac{1}{1/2^{12}} = 2^{12}$	$20 \log 2^{12} =$
" 16 bit "	$\frac{1}{1/2^{16}} = 2^{16}$	$20 \log 2^{16} =$

to achieve the cleanest signal

→ make sure that the analog signal going into an ADC is making full use of the dynamic range of the converter

⇒ between sensor and ADC

<u>amplifiers</u>

ex. single computer chips, large instrument amplifier

dependent on the nature of the signal from the sensors

amplification of

voltage amplifiers are the most common type

amplification of

convert a current to a voltage by means of a transimpedance amplifier

amplification of

ex. capacitive sensors such as piezoelectric devices

convert a charge signal to a voltage

ex. operational amplifiers with feedback capacitors and a capacitor to ground in parallel with the charge source

<u>amplifier hardware specifications</u>

linearity, gain factor, frequency response, stability, accuracy.

desire adjustable gain over a wide range, wide bandwidth over which there is little distortion, and high stability

11.3 Novel Sensing/Actuation Techniques

cf. conventional (direct) techniques

a change in capacitance → an associated change in voltage

→ the voltage signal is directly monitored

novel (indirect) techniques

enhancing the performance : improving

frequency detection (§11.3.1)

sensing frequency shifts rather than voltage, current, or charge

time of flight method (§11.3.2)

sensing lapsed time rather than " " "

∵ frequency and time can be measured most accurately and economically of all of the parameters

11.3.1 frequency detection schemes

frequency shift in a resonant circuit or structure

change in the value of capacitance or inductance dynamically

→ shift in the oscillator frequency → sense using a frequency counter circuit

resonant frequency of a simple oscillator circuit

$$\omega_n = \sqrt{\frac{1}{LC}} \qquad L: \qquad C: \tag{2}$$

cf. $\omega_n = \sqrt{\frac{k}{m}}$ in a mechanical oscillator

nonlinear relation

linear approximation

$L = L_0\,(1+\alpha)$ & $C = C_0$ or $L = L_0$ & $C = C_0\,(1+\alpha)$

L_0, C_0 : nominal circuit values of inductance and capacitance

α : fractional variation in the transducer property,

$$\omega_n + \Delta\omega_n = \sqrt{\frac{1}{L_0\,C_0\,(1+\alpha)}} = \sqrt{\frac{1}{L_0\,C_0}}\,(1+\alpha)^{-\frac{1}{2}} \approx \sqrt{\frac{1}{L_0\,C_0}}\,(1-\frac{\alpha}{2}) \tag{3}$$

$$\Rightarrow \quad \Delta\omega_n \approx -\frac{\alpha}{2}\sqrt{\frac{1}{L_0\,C_0}} \quad \propto$$

linear relationship between the change in the resonant frequency and the change in the transducer property

the linear approximation gets better as $L_0\,C_0$ increases

Example. odor sensor Fig. 11.9

a quartz crystal is loaded by a membrane with a selective ability to adsorb odorants

adsorb odorant molecules → increase membrane mass →

$\Delta\omega_n \propto$ odorant mass per unit area

Doppler shift

particularly useful for determination of linear velocity

⇒ basis for laser Doppler velocimeters,
some ultrasonic flowmeters
radar speed guns

a wave striking a moving (receding or approaching) object

→ spread out (or compress) wavefronts

→ change in the apparent frequency ∝

apparent frequency f' for waves in a real medium (ex. sound, light)

sound

$$f' = f\,\frac{1 \mp u/c}{1 \pm v/c} \tag{4}$$

light

$$f' = f\,\sqrt{\frac{1 \mp v/c}{1 \pm v/c}} \tag{5}$$

f : driving frequency
v : speed of the moving object
c : wave speed in the

Example. laser Doppler velocimeters Fig. 11.10

fluid particles reflect light → multiple light beams produce interference fringes

motion of the fringes ∝ of the particles

11.3.2 lapsed time detection

time-of-flight measurement

used in a variety of applications

from thickness gauges to flow measurement

measurand affect the time required for something to happen

Example 1 automatic focusing transducers in Polaroid cameras

generate a sound → simply monitor the time lapsed for a return echo

→ calculate the distance to the object with known speed of sound

Example 2 ultrasonic thickness gauging

(same principle as Ex. 1)

Example 3 ultrasonic flowmeters   Fig. 11.11

$$t = \frac{L}{c+v} \qquad (6)$$

L : distance, v : fluid velocity, c :

using two pairs of sensors and sources

→ detect difference in the lapsed time

→ produce a twofold increase in the linear signal

Example 4 magnetostrictive position sensor

depends on relative motion between the source and receiver

a short current pulse run through a magnetostrictive waveguide

→ establish a magnetic field

→ interact with the external magnet

→ induce stresses in the waveguide

→ launch an elastic wave

→ sense at one end of the

time from the current pulse to the elastic wave detection

∝   of the external magnet

comments :

Lapsed time and frequency sensing approaches can be used with virtually any of the transducers described in the text book.

These techniques offer an alternative to direct sensing of currents, voltages, or charges, and are useful in many circumstances

11.4 Spatially Distributed Transducers

arrays of transducers

multiple transducer elements arranged in lines, rings, planes, (3-D) spheres, etc.

the most common reason of arrays

to gather (or produce) more than one signal simultaneously and

to introduce an ability to sense (or generate) signals with nonuniform directional distribution

Ex.1 optical encoder Fig. 11.4

permit multiple signals to be gathered simultaneously

multiple optical sensors, each corresponding to one bit of information

Ex.2 linear array of microphone Fig. 11.12

provide directional information

maximum output for the sound approaching at θ = and gradually decreases with the angle increases

the output is very much a function of the manner in which the multiple signals of the transducer elements are combined to form a single array output

ex. in Fig. 11.12

the signals from the element of the linear array

can be amplified with differing amounts of gain or

can be delayed by differing amounts of time

the spacing between the elements can be intentionally made nonuniform

a single transducer with large spatial extent

Ex.1 a microphone Fig. 11.13

replaces a linear array of 28 microphones

sensitivity is effectively varied as a function of position by varying the

Ex.2 viscosity sensor with a torsionally vibrating rod

11.5 Summary