Unit-5

Smart Sensors

Introduction of smart sensors Imp

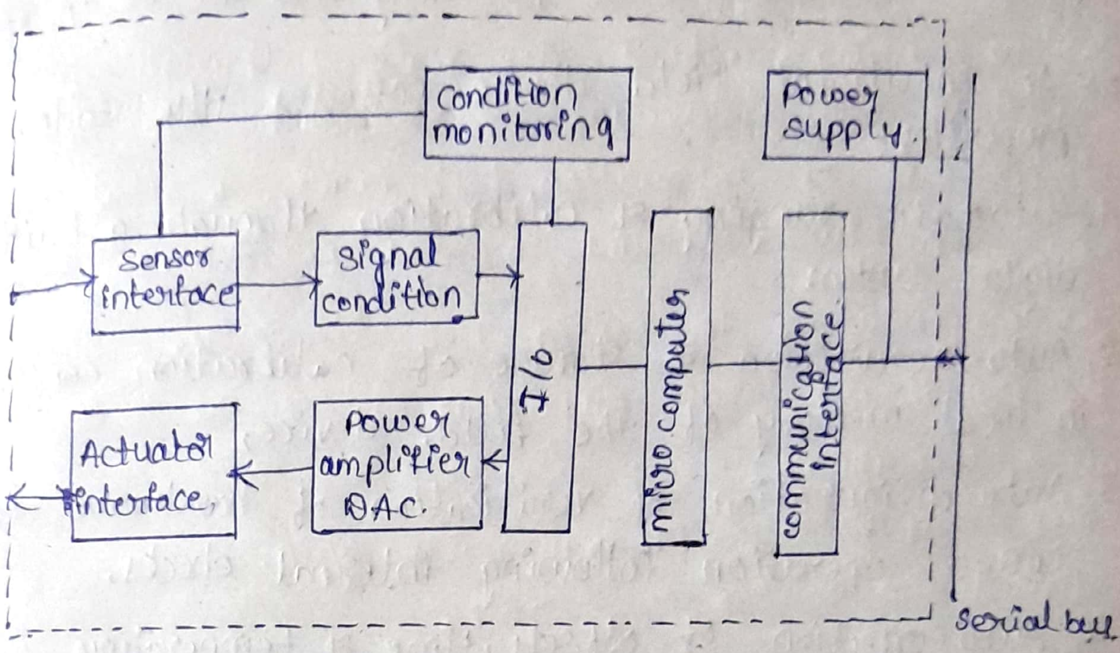


Fig (a) Typical intelligent sensor & actuator.

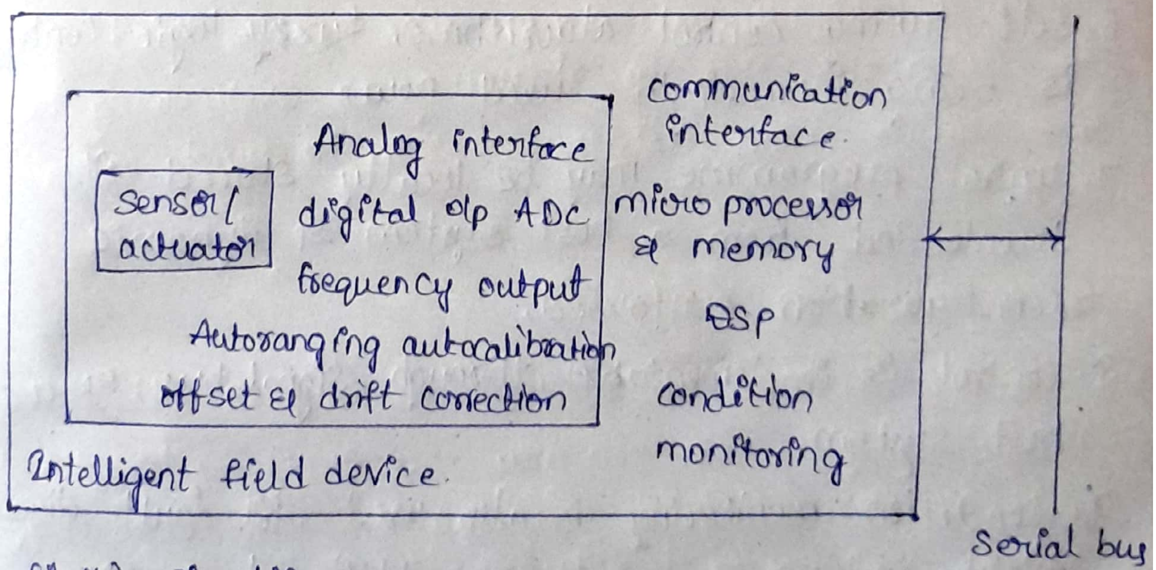


fig (b) simplified version of (a)

⇒ A sensor producing an electrical output when combined with interface electronic circuits is said to be an intelligent sensor if the interfacing circuits can perform (a) ranging (b) calibration. & (c) decision making for communication & utilization of data.

⇒ Both sensors & actuators are used as intelligent Components of instrumentation systems. Infact they are used as field devices. The block diagram of one such intelligent equipment is shown in above figures (a) & ~~(b)~~. figure (b) shows the ~~sp~~simplified version with facilities of processing that can be incorporated.

⇒ An intelligent field device possesses the following properties:

1. Automatic ranging & calibration through a built-in digital system
2. Auto-acquisition & storage of calibration constants in local memory of the field device,
3. Auto configuration & verification of hardware for correct operation following internal checks,
4. Auto correction of offsets, time & temperature drifts.
5. Auto linearization of non linear transfer characteristics,
6. self-tuning control algorithms, fuzzy logic control is being increasingly - used now,
7. control programme may be locally stored or downloaded from a host system & dynamic reconfiguration performed,
8. control is implementable through signal bus & a host system
9. Condition monitoring is also used for fault diagnosis which, in turn, may involve additional sensors, digital signal processing & data analysis software
10. Communication through a serial bus.

⇒ Intelligent sensors are also called smart sensors which is more acceptable term now. The initial motivation behind the development of smart sensors include (i) compensation for the non-ideal behaviour of the sensors & (ii) provision for communication of the process data with the host system

=> Advanced processing technologies have now replaced earlier ones used for developments of smart sensors. Sensor elements are open to process although they are now being built in the smart system itself. Certain sensors require supply, constant voltage or constant current along with comparison capabilities, the feature is included in sensor subsystem. A

=> Amplification is necessary which usually analog, may also be controlled digitally. Earlier anolg filters were employed which have now been replaced by digital counterparts. These three systems, namely the supply, amplification, & filters, comprise the analog signal processing unit (ASPU).

=> Smart sensor also requires a data conversion module either from analog to digital (A/D) or from frequency to digital (F/D) which interfaces with the microprocessors for information processing & bus interfacing for communication.

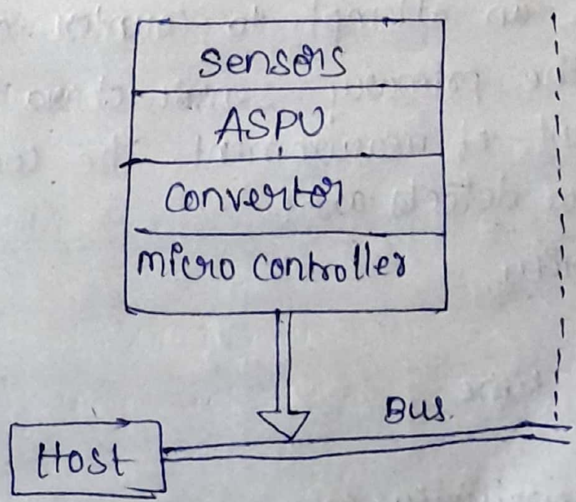


fig: A sensor interfaced with a host system.

⇒ The smart sensor devices integrate complementary trends such as.

(a) new sensing methods
(b) improved computing capability, and
(c) digital communication.

⇒ New sensing methods are realized through synthesis of those from individual sensors with combined technologies & integration techniques. Digital correction in such new techniques improves performance by.

(i) compensating for sensor non-linearity.
(ii) permitting a larger proportion of sensors to meet specifications,
(iii) incorporating programmable gain,
(iv) changing sampling rate,
(v) changing interaliasing filter frequency, & so on.

⇒ Digital communication, on the other hand, plays an important role in reducing or overcoming noise and ~~quati~~ quantification errors to send error-free data.

Compensation Imp

⇒ Compensation is an attempt to counter all sorts of non-ideality in the primary sensor characteristics as well as envirorment of measurement. The commonly encountered sensor defects are:

(a) non linearity.
(b) noise.
(c) response time
(d) drift
(e) cross sensitivity &
(f) interference.

⇒ Manufacturing tolerance may be combined under drift whereas temperature and/or other environmental effects are accommodated in noise.

Non linearity

⇒ Analog processing shows serious nonlinearity which at one time, was solved by piecewise linear segment approach modelled by linear electronic circuits

⇒ With digital processing methods in use now, more readily available general techniques are there to be used for the purpose.

⇒ one very common technique is to refer to look-up tables while others are polygon interpolation, polynomial interpolation and cubic splines interpolation techniques of curve fitting.

a: look-up table method:

⇒ In this method, the sensor characteristic is described by a number of reference points very close to each other which are stored in ROM with linearized values.

⇒ Response of the sensor for a measured value is refered to the ROM to look up for the corresponding linearized value which is then passed on for display or further processing.

⇒ For good accuracy, this requires a large storage capacity or memory.

b: polygon interpolation:

⇒ It is intended for soft nonlinearity where sectionalized linearization can be adopted.

⇒ This ~~as~~ method assumes that the nonlinear range is divided into a few linear sections & hence, a fewer reference points serve the purpose of linearization since between these stored reference points, the ~~t~~ sensor is considered to behave linearly.

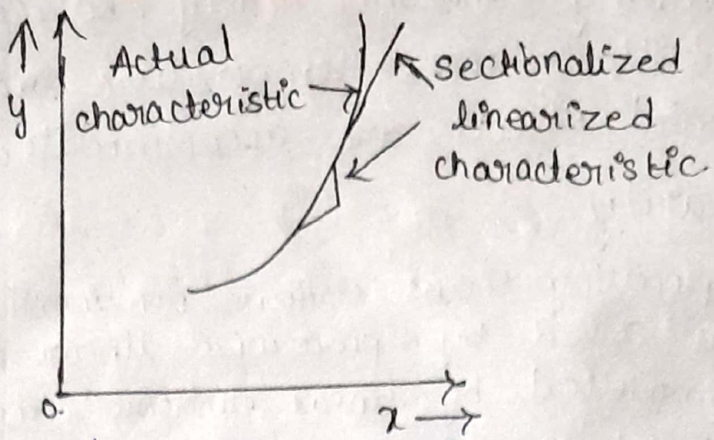


Fig: polygon interpolation.

C: polynomial interpolation:

⇒ This technique is again a standard technique which is based on the functional relationship between n selected measured points on the sensor characteristics and a polynomial of order $\leq (n-1)$ over the range covering the characteristics.

⇒ Lagrange's interpolation technique is a very common such technique. The curve is represend by the formula

$$y = \sum_{i=0}^{m} a_i x^i$$

⇒ the modification of this method for full-scale linearization is to generate a complementary curve for this characteristic as.

$$y_c = \sum_{j=0}^{m} b_j x^j$$

⇒ And then, obtain the arithmetic, geometric or root mean square mean as,

$$y_{linear} = \frac{1}{2}(y + y_c)$$

$$y_{linear} = (y y_c)^{1/2}$$

or

$$y_{linear} = \left[\frac{y^2 + y_c^2}{2}\right]^{1/2}$$

⇒ The below graph shows the linearization principle graphically. The polynomial interpolation method is usable under limitations of order. Increase in order often leads to oscillations.

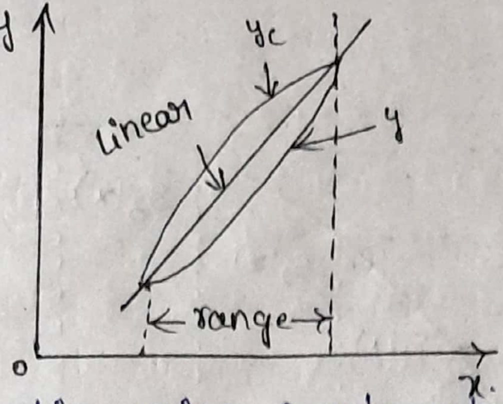


fig: Linearization using complementary function.

d: cubic spline interpolation:

⇒ This method is so named as the sections of the characteristic curve of the sensor between a selected pair of reference (measured) points are represented by cubic spline function as

$$S_i(x) = a_i + b_i(x - x_i) + c_i(x - x_i)^2 + d_i(x - x_i)^3.$$

with $x \in [x_i, x_{i+1}]$ & $i = 0, 1, 2 ---- (n-1)$.

⇒ Each section on two sides, expect the first & the last sections in below figure which have one end free, have function points that are also represented by the adjacent spline functions.

⇒ Both these functions must coincide with each other in function values, gradient, & curvature at these points, from which, conditions for the polynomials are derived.

⇒ The end-points or the range binding points possess separate features – often it is considered that at these points, curvature is zero. with all these specifications, we obtain.

$$S_i(x_i) = y_i \quad , \quad i = 0, 1, --- n;$$

$$S_i(x_i) = S_{i-1}(x_i), \quad i = 0, 1, ---- n, \text{ for function values;}$$

$$S_i'(x_i) = S_{i-1}'(x_i), \quad i = 0, 1, --- (n-1), \text{ for gradients;}$$

$$S_i''(x_i) = S_{i-1}''(x_i), \quad i = 0, 1. ---- n-1, \text{ for curvatures;}$$

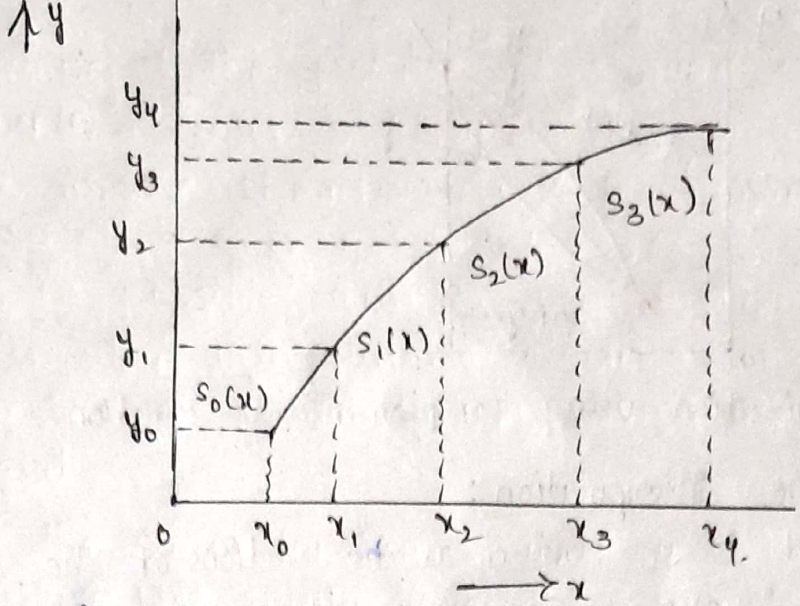


fig: Cubic spline interpolation.

⇒ ~~fo~~ It is advantageous to choose y-direction increments equal for the reference points & from the given conditions, the coefficients are evaluated.

⇒ Basically, interpolation is to fit a polynomial through the points around the point y where the function value is to be found.

⇒ This polynomial is an approximation of the function & is used to find f(x).

Assuming a second order polynomial of the form.

$$f(x) = a_1(x-x_2)(x-x_3) + a_2(x-x_1)(x-x_3) + a_3(x-x_1)(x-x_2)$$

even by inspection, one easily gets

$$a_1 = \frac{f(x_1)}{(x_1-x_2)(x_1-x_3)} \qquad a_2 = \frac{f(x_2)}{(x_2-x_1)(x_2-x_3)}$$

$$a_3 = \frac{f(x_3)}{(x_3-x_1)(x_3-x_2)}$$

So that the n^{th} polynomial can be expressed as

$$f(x) = \sum_{i=1}^{n+1} f(x_i) \prod_{\substack{j \neq i \\ j=1}}^{n+1} \frac{(x-x_j)}{(x_i-x_j)}$$

which is known as the lagrange's polynomial.

Noise & Interference

⇒ Thermal noise is important in almost all sensors. Besides, there are other unwanted signals that may be picked up due to external magnetic fields when the structure is not adequately screend

⇒ Noise is also introduced at different stages of signal processing such as data conversion, analog to digital interfacing by stray effects & so forth.

⇒ The methods of minimization of noise are appropriate signal conditioning techniques that include filtering, signal averaging & correlation among others.

⇒ If the signal is periodic as in the case of output of the frequency converter, the correlation technique improves the signal-to-noise ratio by a large value. This is due to the superposition property of autocorrelation.

⇒ Again, if the input is corrupted at any stage by noise, specifically white noise, a cross correlation technique can be used to obtain the system response/ function without this corruption.

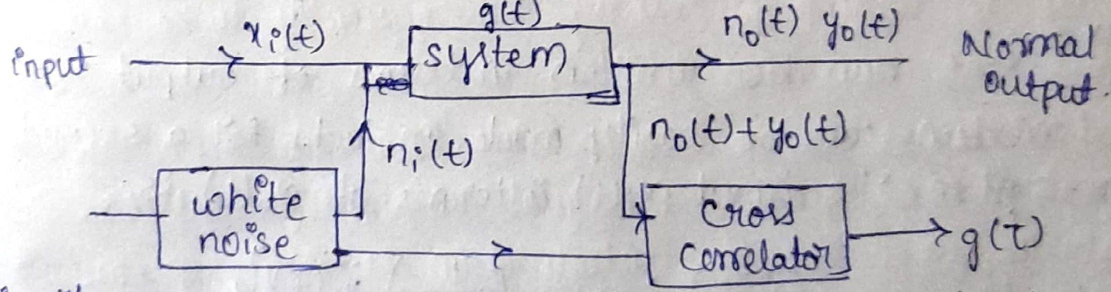


Fig: The cross correlation technique for noise reduction

⇒ For a signal $f_1(t)$, the autocorrelation function is

$$\phi_{11}(\tau) = \lim_{T\to\infty} \left(\frac{1}{2T}\right) \int_{-T}^{T} f_1(t)\, f_1(t+\tau)\, dt.$$

⇒ If the output for a signal $f_1(t)$ is $f_0(t)$, the cross correlation function is

$$\phi_{12}(\tau) = \lim_{T\to\infty} \left(\frac{1}{2T}\right) \int_{-T}^{T} f_1(t-\tau)\, f_0(t)\, dt.$$

Response Time

- ⇒ Because of the presence of storage & dissipative elements, a sensor is likely to have quite inferior time response characteristics & the 'dynamic correction' of sensor becomes necessary.
- ⇒ This is possible with the use of microprocessors/micro computers with suitable algorithm if the dynamic parameters are known through solving the convolution integral
- ⇒ If the sensor function is given by $f(s)$, the signal processing unit should have a function $1/f(s)$ as shown in below figure, so that we obtain.

$$x_i(t) = \int_0^1 x_o(t-\tau)\, g(\tau)\, d\tau = x_o(t) * g(\tau)$$

where $g(\tau) = L^{-1}\left\{\frac{1}{f(s)}\right\}$

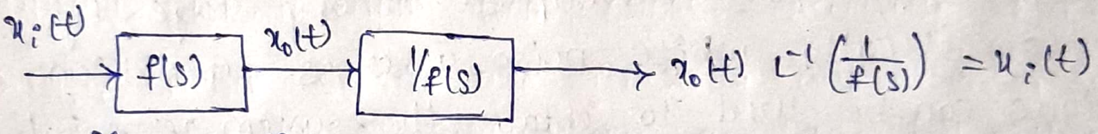


fig: Cascading complementary processing function.

where $x_i(t)$ can be written in terms of output $x_o(t)$, the correction can be easily made. In fact, for a second order system, the input $x_i(t)$ in terms of $x_o(t)$ is.

$$x_i(t) = \frac{1}{K}\left\{ x_o(t) + \left(\frac{2\xi}{\omega_0}\right)\dot{x}_o(t) + \left(\frac{1}{\omega_0^2}\right)\ddot{x}_o(t)\right\}$$

where. ξ = damping factor

ω_0 = natural frequency of oscillation

$x_i(t)$ = expressed in terms of the output & derivative

$\dot{x}_o(t)$ & $\ddot{x}_o(t)$ = reference points.

Another method using the difference equation is also useful in digital systems for obtaining $\dot{x}_o(t)$ & $\ddot{x}_o(t)$ as

$$\dot{x}_o(t_j) = \frac{1}{T_s}\left[x_o(t_j) - x_o(t_{j-1})\right]$$

&

$$\ddot{x}_o(t_j) = \frac{1}{T_s}\left[\dot{x}_o(t_j) - \dot{x}_o(t_{j-1})\right]$$

Drift

⇒ Drift appears in a sensor because of slow changes in its physical parameters either due to ageing or deterioration in ways of oxidation, sulphation & so on.

⇒ Drift is a kind of noise & should be counteracted.

⇒ As drift tends to change the sensor characteristics, the reference points for polynomial interpolation also tend to drift.

⇒ These are required to be updated and hence, the co-efficients are re-evaluated through an algorithm.

Cross-Sensitivity

⇒ A sensor, while responding to a specific variable, responds to others as well, may be, with much less sensitivity.

⇒ It is therefore necessary to maximize the sensitivity for the desired measured & minimize that for the others.

⇒ A common undesired interfering variable is temperature for non-thermal sensors.

⇒ If the interfacing variable is defined as z, output as y & measured as x, then the nominal or rated z, z_0 is taken as the base value of the interfering quantity while with varying z_0 from z, the characteristics are changed as shown in below figure.

⇒ The function $y(x,z)$ can be expressed as a series of the base characteristics $y_0(x, z_0)$ given by.

$$y(x,z) = \alpha_0(z) + [1+\alpha_1(z)]\, y_0(x, z_0) + a_2(z)\, y_0^2(x, z_0) + $$

⇒ For $z = z_0$ the function $\alpha_i(z)$, $i = 0, 1 \ldots n$ becomes zero, otherwise it describes the effect of interference by z. This function $\alpha_i(z)$ can be written as a polynomial function that can be written as.

$$x_i(z) = \sum_{j=1}^{m} B_{ij} (x - z_0)^j$$

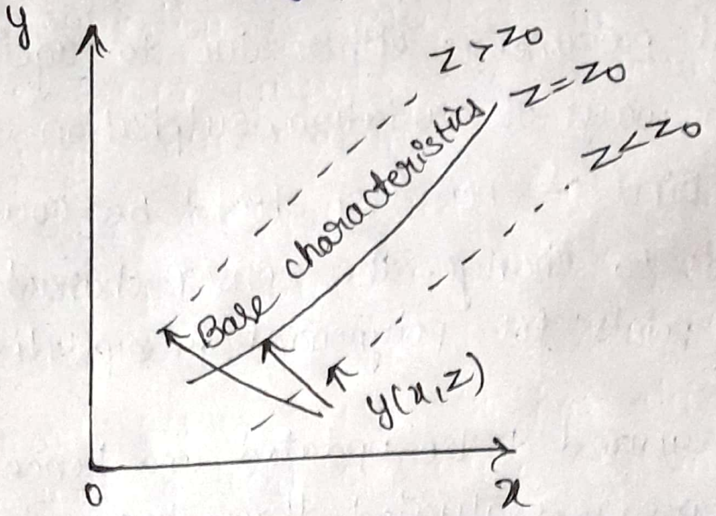


fig: curves pertaining to analysis of cross sensitivity.

Information coding / processing

⇒ It has so long been assumed that signal from a sensor is processed providing correction, compensation, linearization, freedom from cross-sensitivity & drift.

⇒ The smart sensors are generally multi-sensor systems and a number of signals are available for either display or further processing subsequently to be connected to the 'communication bus.'

⇒ The state of the process in the form of a processed signal through sensor & signal processing systems, is first received by the information coding system.

⇒ Some of these signals are released, some stored, some destroyed & some restructured.

⇒ For indication purposes only, the signals are coded & displayed over appropriate display modules as is done in digital meters, indicators, recorders. A typical IC temperature sensor-based smart sensor is depicted by below figure.

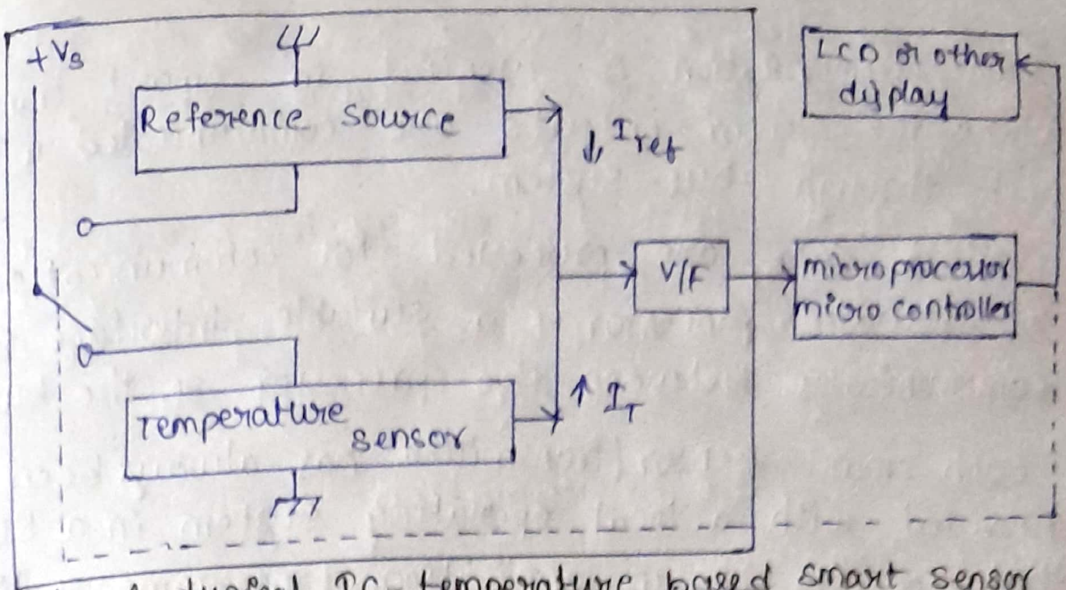


fig: A typical IC- temperature based smart sensor

- When these signals are required to be used for system control & surveillance as is usually the case, in addition to display, control system should be able to read the signals for their functioning.

- Information processing assembly in a smart sensor is basically an encoder, the encoded data from this are fed to the communication unit. The conventional signal processing provides an output of 4-20mA.

- One way to get a corresponding voltage range which is then parallelly encoded into digital signal through a converter.

- voltage-to-frequency converter is another kind which is quite extensively used, then using a reference frequency generator, frequency difference encoding is employed

- the ratio control of a square wave is another coding technique but not often restorted to.

- There are many other techniques & choice is largely based on the specific requirement & associated conditions.

Data Communication

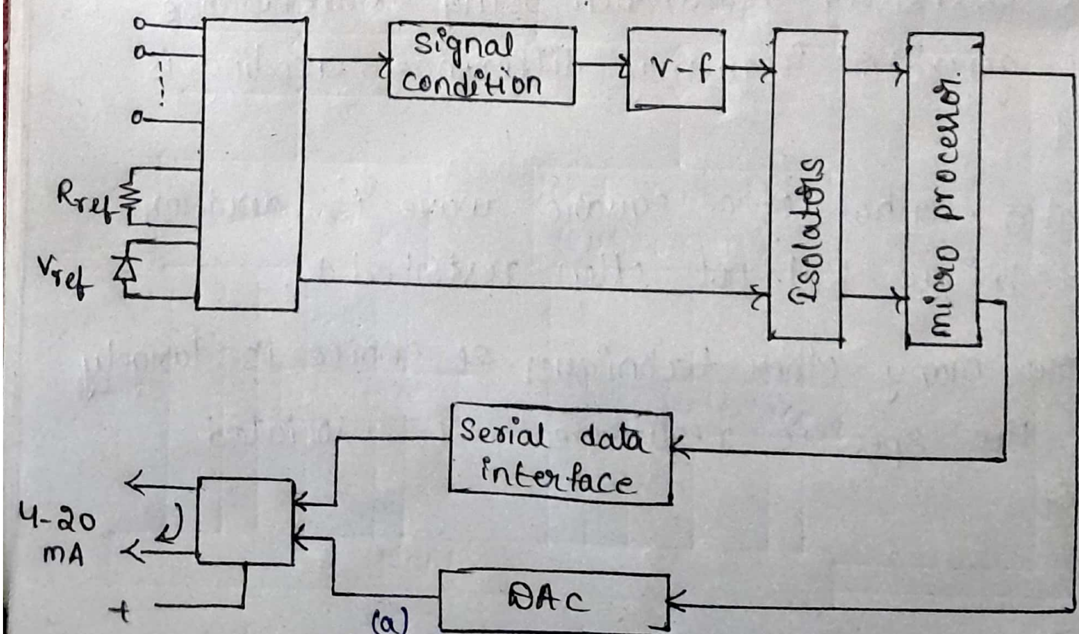
⇒ Data Communication is essential in smart transmitters where the sensor outputs are communicated with the host through bus-system.

⇒ Coded data are processed for communication by a software processor & a suitable interface system communicates between the processor & the bus.

⇒ Each smart sensor/transmitter has always been provided with a local operating system in a ROM, that consists of an application programme & library modules, for ADC & DAC hardwares, bus driving hardware, local interface hardware, & LCD/keyboard hardware.

⇒ Earlier manufacturers preferred to develop their own protocol. One such protocol is HART (Highway Addressable Remote Transducer) offered by Rosemount which superposes a digital transmission protocol on the standard 4-20 mA loop.

⇒ A typical transmitter with HART protocol appears as shown in below figure. Some other protocols that find use are High level Data link Control (HDLC), Synchronous Data Link control (SDLC), Factory Instrumentation protocol (FIP) & so on which are sufficiently advanced.



(a)
fig: A smart transmitter.

=> The HART protocol has been designed for direct use of 4-20 mA output device having facilities of digital communication with superimposed modulation between the field device & a host system. Such devices can be connected in parallel.

=> The addressing procedure allows each unit to set its output for power supply at 4mA & the device is forced to communicate only digitally.

=> The parallel connection converts the twisted pair into a multiloop bus but the number is limited to 15 as specified by this protocol. The power source, therefore, supplies a maximum of 60mA.

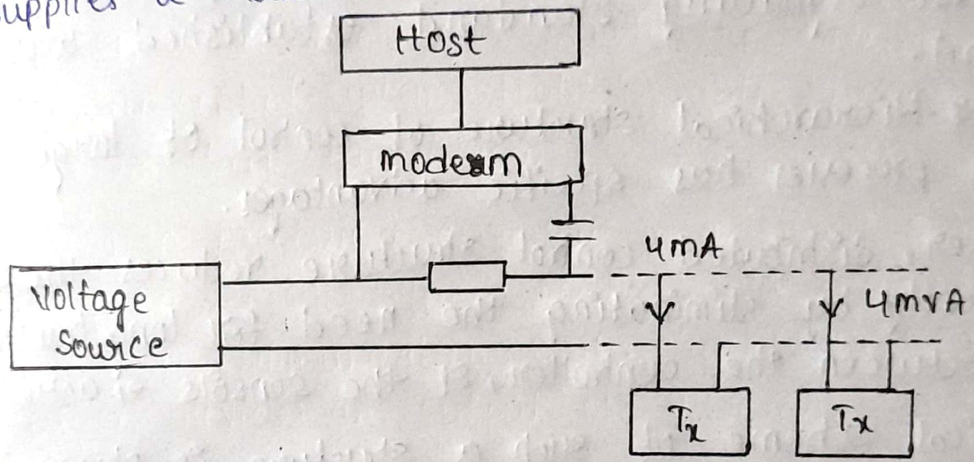
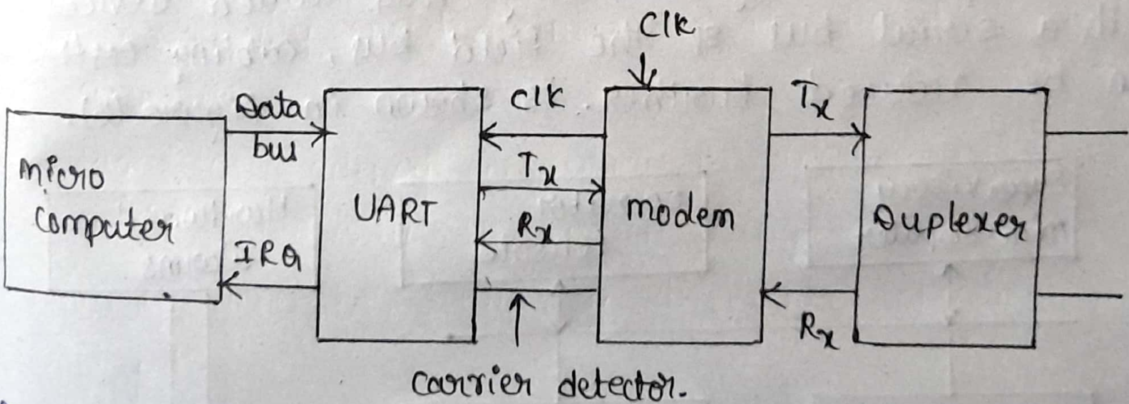


fig: (b) The basic multiloop connection.



Fig(c): Demonstration of hardware requirement of an intelligent field device.

=> In HART protocol, it is the master-slave proposition that works - the field device responds only when it receives instruction from the bus & in every reply message, the status of the field device is included to check its state.

⇒ Application specific integrated circuits (ASIC) are receiving attention more & more for the internal operation of the sensor & signal processing system of the smart sensor.

⇒ ASIC & its supporting technology make available a host of ready items from which those required can be selected, incorporating variety in the smart sensor design & enhancing its capability.

The Automation

⇒ In modern control systems, signal communication standards have been of tremendous significance. The first signalling standard established was 4-20 mA.

⇒ In 198 Hierarchical structure of control of large complex processes has specific advantages.

⇒ However, distributed control structure reduces the cost significantly by eliminating the need for long transmission lines between the controller, & the sensors & actuators.

⇒ A typical scheme of such a structure is shown in below figure (a). By connecting field-located devices with a serial bus & the field bus, cabling costs can be reduced further. is shown in figure (b).

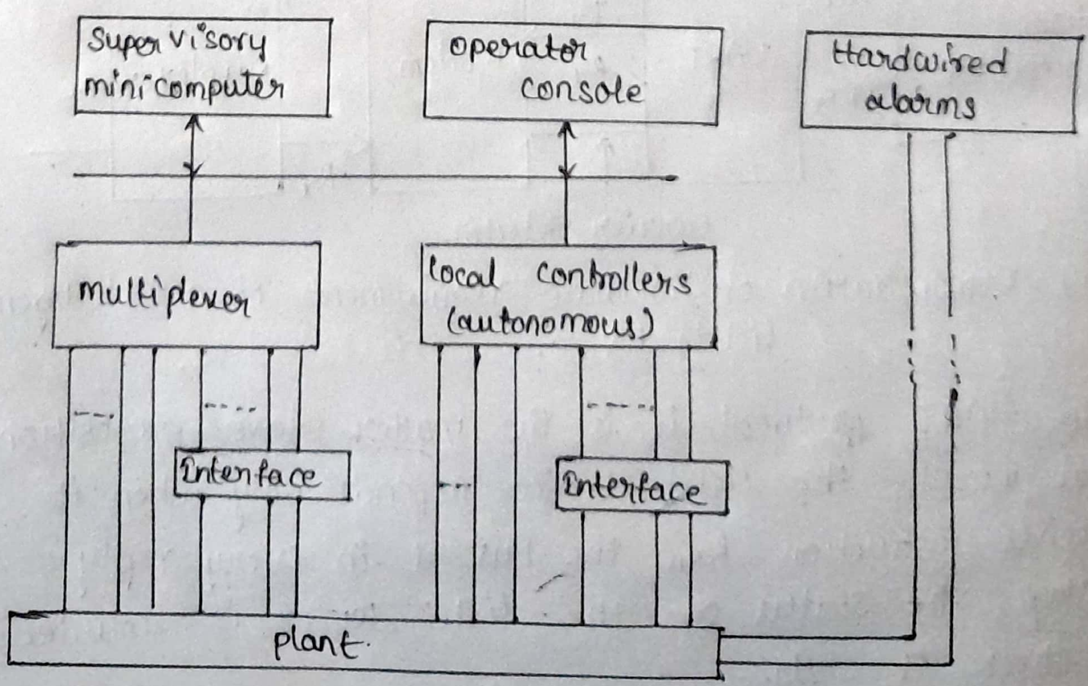
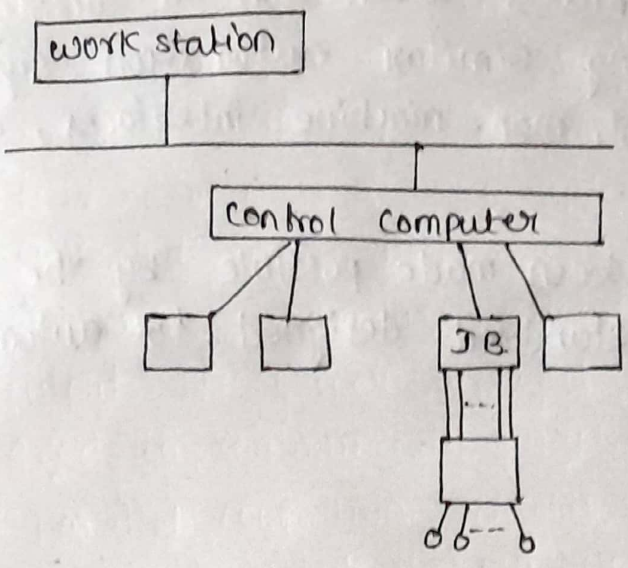
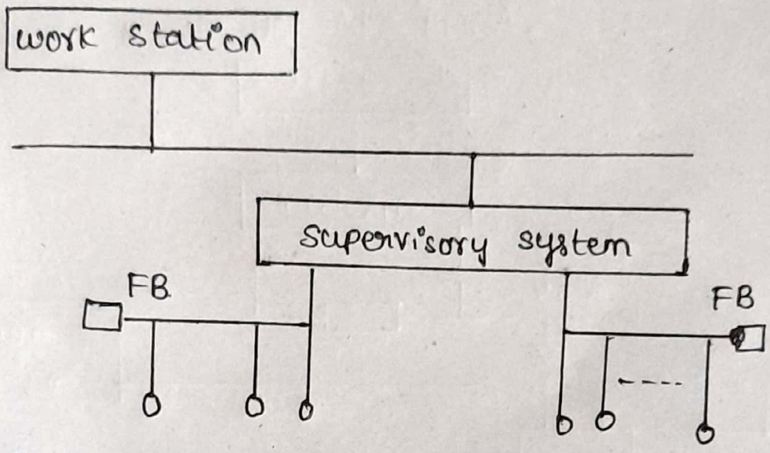


fig (a) : Distributed control structure.



fig(b): Instruments & actuators star-connected to junction box (JB).



Fig(c) Intelligent instrumentation & actuators linked by a field bus system.

⇒ Automation entered the area of flexible manufacturing satisfying quality specifications.

⇒ this kind of manufacturing covers the aspects of disciplined production with enforced environmental legislation.

⇒ The advancement of semiconductor technology has paved the way for all these to be integrated & applied at relatively low cost in the industrial processes. Thus, one can represent the system as

Instrumentation + programmability + Communication ⇒ Automation
(negative feedback) Integrated low cost ⇐ semiconductor technology ↵

⇒ In recent years, process automation & factory automation are using similar automation systems for closed loop control, man-machine interfaces, & for networking.

⇒ Such converge has been made possible by the use of IEC field bus standard designed for automation applications.