Instrumentation and Control - Course 136

DIRECT DIGITAL CONTROL OF PROCESSES

The use of a computer in process control gives an added flexibility to the Control Engineer. Improved control techniques have been developed, to improve the control at processes, that cannot be applied, or very inconveniently applied with analog instrumentation.

Usually when DDC is used, it will be employed on a multiple process system, (eg, liquid zone level control) a provision will also have to be made for backup in the event of computer malfunction. In Ontario Hydro this is achieved by using a back-up computer.

Analog and Digital Representation

In order to communicate between the computer and the process instrumentation it is necessary to convert process analog data to digital data and vice versa. Consider a temperature transmitter with a range of 50°C to 150°C. Theoretically the analog signal from the transmitter can vary continuously between 4 mA (at a temperature of 50°) and 20 mA (temperature at 150°).

In practice however the sensitivity of the transmitter is limited. We must specify its resolution (the smallest fraction of range that can be detected and reproduced) and this is typically 0.5% for most analog instrumentation. Note that this is based upon the range, ie, for the range given as an example 0.5% equals 0.5%C. We are not considering the accuracy of the measurement which is a function of the temperature sensing element (thermocouple or resistance thermometer) but only the reproducibility of a given measurement.

In order to store the transmitter output in the computer memory it must be converted to a digital quantity. The analog to digital converter (ADC) is the device that digitizes (into binary form) the analog signal from the transmitter. This conversion process can generally be performed at a much faster rate than the typical process signal can change. It is therefore possible, and less expensive, in a multiple process system to employ a single ADC with a signal selection processs on its input.

The signal selection is generally performed by the combination of a multiplexer and a sample and hold (zero order hold) amplifier. The multiplexer can be visualized as a multiple contact switch, indeed some DDC systems still employ reed relay type multiplexers. More recent types use integrated circuit type analog switches. For both types it is important that the switching action be "break before make" whilst switching between inputs to avoid crosstalk and interaction between inputs. Some form of "store" is therefore necessary to preserve the signal whilst the ADC is disconnected from the input.

This function is performed by the Sample and Hold amplifier. In its basic form the S and H consists of a high input impedance operational amplifier with a capacitor connected across its input. The capacitor will charge to the maximum value of the input signal via the multiplexer. When disconnected from the inputs the capacitor will retain its charge (remember high input impedance - low discharge rate) and continue to supply the input signal to the operational amplifier and therefore an output signal which can be routed to the ADC.

The resolution of the digitized output of the ADC is determined by the number of bits generated. Each bit, or binary digit, can have only two values, 0 or 1. Since n bits are capable of generating 2^n states, the resolution is given by 2^{-n}. For example if the ADC had only one bit, it could only tell us if the temperature is in the lower half of the range (value = 0) or in the upper half (value = 1), thus we would have a resolution of 0.5 or 50%.

In practice process ADC's have eleven or twelve bits with resultions of 0.05% (1 part in 2048) or 0.0025% (1 part in 4096). Clearly an eleven bit ADC is more than adequate for the analog data which is required to be digitized. The following table illustrates the output of the ADC for the temperature range under consideration (50-150°C).

T°C	Transmitter Output (mA)	ADC Output (11 Bit)
50	4.0	00000 000 000
75	8.0	01000 000 000
100	12.0	10000 000 000
125	16.0	11000 000 000
125.05	16.008	11000 000 001
149.95	19.992	11111 111 111

The digital information is now inputted to the computer. The appropriate control correction can now be applied (via a suitable algorithm) and the modified (digital) information can be output to the final control device.

Digital to Analog Conversion

The final control device is an analog device (most often a pneumatically operated control value) and it is therefore necessary to effect a further data conversion, from digital to analog.

The digital to analog converter (DAC) is invariably a simpler (and therefore cheaper) device than the ADC and in a multiple process application is usual to employ one DAC per process rather than another multiplexer and a single DAC. The output from the DAC can be in one of two basic forms:

1. Track and Hold, where the analog output is updated periodically to a value coresponding to the digital output from the computer and held constant until the next update time.

2. Integrating Station, where the analog output is incremented or decremented at each update by an amount corresponding to the change in computer output and held constant until the reset update time.

For the first type the computer must output the desired value of the signal while for the second the computer output is the change in the signal.

The converter signal must now usually be routed to an electric to pneumatic converter (I/P) if a control valve is being used as a final control element. The complete system is shown in Figure 1.

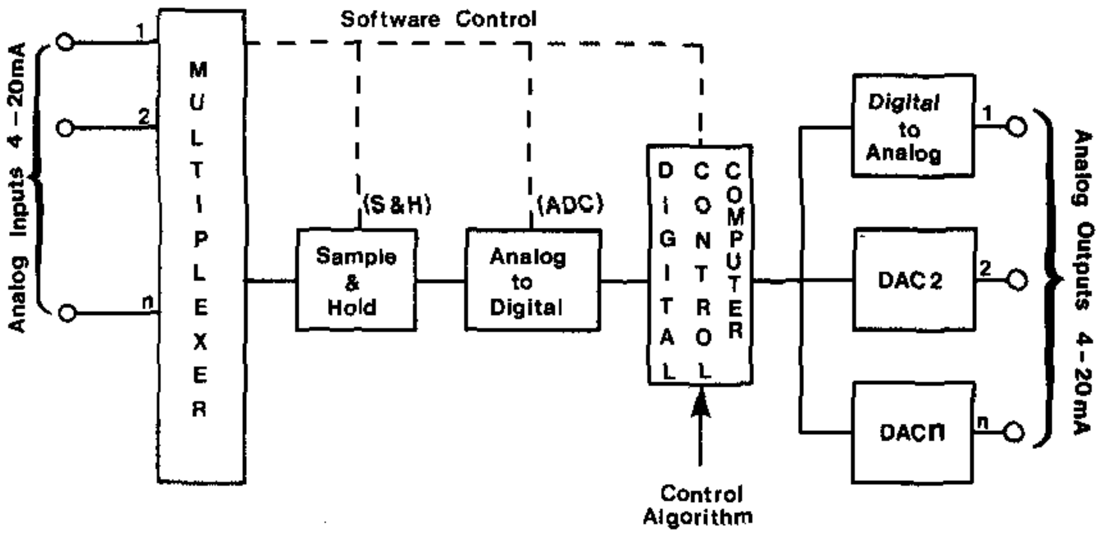

Figure 1: Representative Multiple Process Using Direct Digital Control.

Digital Computer Control Techniques

The digital computer is capable of performing all of the basic control functions previously reserved for analog instrumentation. These include feedback, feed forward and cascade control and in many instances the computer offers advantages in the degree of control possible.

Feedback Control

The equation for a Proportional - Integral - Derivative (PID) controller can be given as:

$$m = \frac{100}{PB}\left[e + \frac{1}{R}\int_0^t e\,dt + D\frac{de}{dt}\right]$$

where,
m = controller output signal
e = error signal = setpoint - measurement
$\frac{100}{PB}$ = K = controller gain
1/R = reset rate
D = derivative time

The digital computer can perform the PID controller calculation for as many loops as necessary. However in order to do this, the measured variables must be sampled at uniform intervals of time and digitized for storage in the computer memory. This means that the measured variable is not available to the computer as a continuous function of time but as discretely sampled values. This can be graphically sketched in Figure 2.

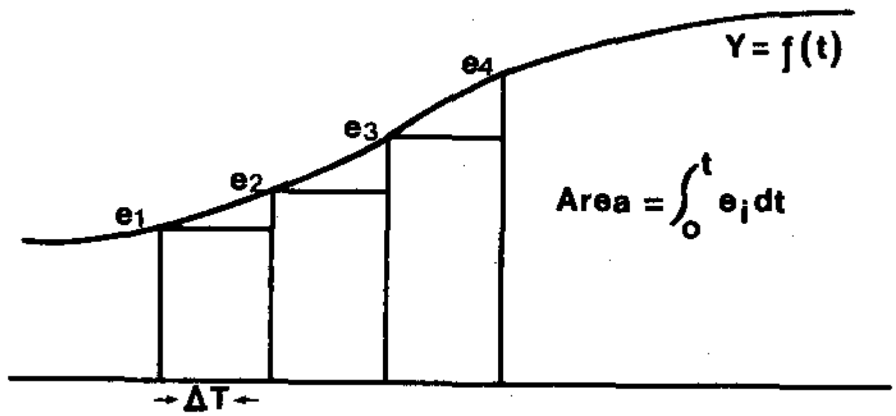

Figure 2: Sampled Analog Singal.

T is the time interval between samples or sample time. Note that there is a loss of information in sampling, namely the response between samples. Since the measured variable is only available at the sampling instants, the error and the controller output can only be computed at these times.

The computer can perform continuous integration by assuming the curve to be integrated, Y = f(t) is made up of a large number of rectangular sections each of width T. Each segment has the area e.T and the integral is given by:

$$I = \sum_{i=0}^{n} e_i T_i = T \sum_{i}^{n} e_i$$

where, e = SP - Measurement

We need therefore only add up the discrete values of e at the start of each time interval T and multiply the sum by T. As T is made smaller the approximation becomes more accurate.

It can be seen from the diagram that there is a small residual error in this approximation. (The approximately triangular area between the top of the rectangle and the true curve.) This area is given by:

$$e_{(n+1)} - e_n.T/2 = \Delta e.T/2$$

A more accurate integration formula is therefore:

$$I - \sum_{i=0}^{n} (e + \Delta\frac{e}{2}).T$$

If this equation is used, the sampling period can be increased.

Differentiation is accomplished as shown in Figure 3.

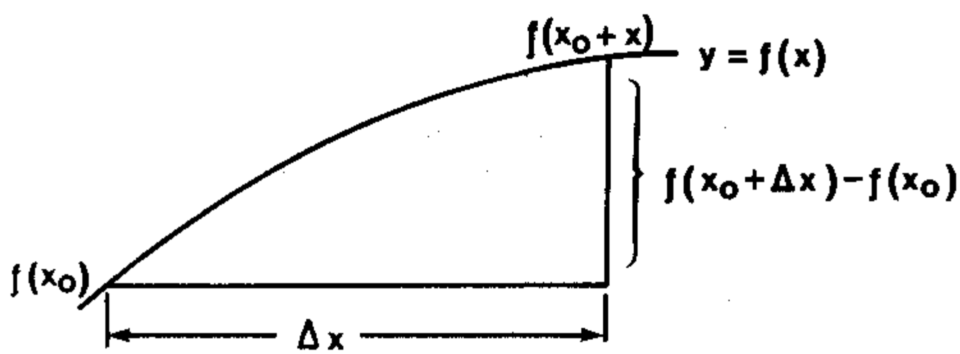

Figure 3: Differentiation Process.

$$\frac{de}{dt} = \frac{e_n - e_{(n-1)}}{T}$$

The complete PID control algorithm now becomes (using the basic integration format):

$$M = B + Kc[e_n + \frac{T}{T_i} \sum_{i=0}^{n} ei + \frac{TD}{T} (e_n - e_{(n-1)})$$

where, m = process value
B = steady state value (bias)
K_c = controller gain
T_i = rest time
T_D = derivative time
T = sampling time

This version is known as the position form of the algorithm because the effective valve position is calculated. A more popular version can be derived from it by considering the equation at previous sample.

$$m_{n-1} = \overline{m} + K_c[e_{n-1} + \frac{T}{Ti} \sum_{i=0}^{n-1} ei + \frac{TD}{T} (e_{n-1} - e_{n-2})$$

Subtracting this equation from the previous one:

$$\Delta m_n = m_n - m_{n-1} = K_c[e_n - e_{n-1} + \frac{T}{Ti} e_n + \frac{TD}{T} (e_{n-2} e_{n-1} + e_{n-2})]$$

This version is known as the "velocity" form of the algorithm, because the change in valve position per sample is calculated. The computation $m_n = m_{n-1} + \Delta_{mn}$ can be performed in the digital computer itself or in the digital to analog conversion device.

Either form of the PID control algorithm requires seven computer storage locations per loop: the three parameters, the output and either the sum and the two latest values of the error or the three latest values of the error. The initial value of the output B can be converted into an initial value of the sum. The velocity algorithm is easier to initialize.

The PI control algorithm is obtained by setting the derivative time TD to zero. It requires only five storage locations.

The output of the controller must be held by the DAC until the next sample and computation. The shape of the signal from the DAC has the following form.

Disadvantages of Digital Control

1. Sensitivity to noise in the measured variable that requires filtering.

2. Introduction of dead time into the loop which reduces the ultimate gain.

3. Discretization error that cause the derivative action to produce undesirable pulses in the controller output.

Sensitivity to Noise

Consider a continuous signal which contains high frequency noise.

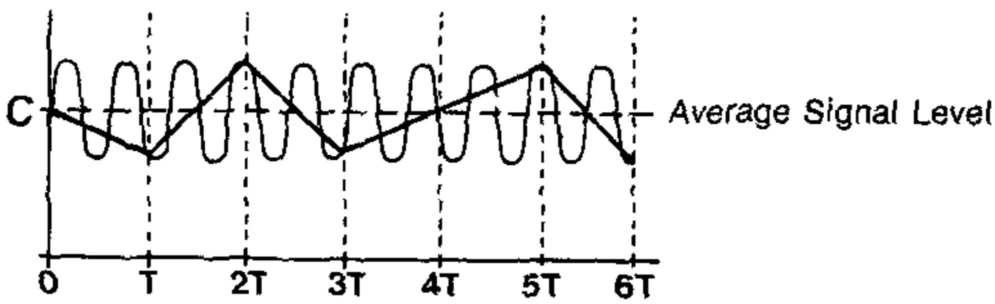

Figure 4: Generation of Low Frequency Noise.

In an analog system the noise content will not generally affect the output because its frequency is too high to force the typically slow analog components. In a digital system however this noise will be sampled at intervals equal to T. It can be seen that a noise signal is generated at a lower frequency than the original noise. This lower frequency noise affects the computer performance because it is in the range of the sampling frequency and therefore in the range of response of the process. This effect is known as aliasing error.

It is therefore necessary to filter the signal before digitizing either by a conventional electronic filter or by a digital (software) filter or both.

The simplest form of digital filter takes the form:

$$V_n = qV_{n-1} + (1-q)w_n$$

where, V_n = filtered variable at nth sample
W_n = input (noisy) variable at nth sample
q = filter parameter ($0 \leq q \leq 1$)

Note that q=0 produces no filtering while q=1 will ignore the input measurement: A typical value of q = 0.15.

Introduction of Dead Time

Recall that the output of the DAC must be held at a steady value between samples. The diagram shows the comparison between a continuous analog ouput and the output from a DAC.

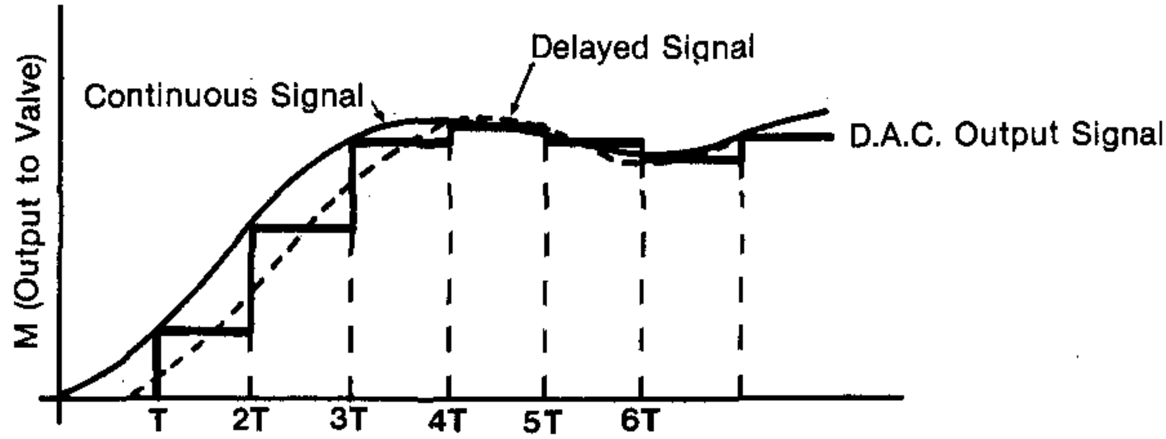

Figure 5: Generation of Dead Time.

Note that the holding operation introduces a dead-time equal to half the sampling interval. This will reduce the ultimate gain of the loop. The effect will be lessened as the sampling frequency is increased.

Discretization Error

This is due to the digitization of the analog measurement. When digitizing a continuous variable there is a minimum threshold (the lowest order bit) below which changes cannot be detected. When the rate of change of the variable is less than one bit per sample, the diagram (Figure 9) represents the contribution at the derivative action.

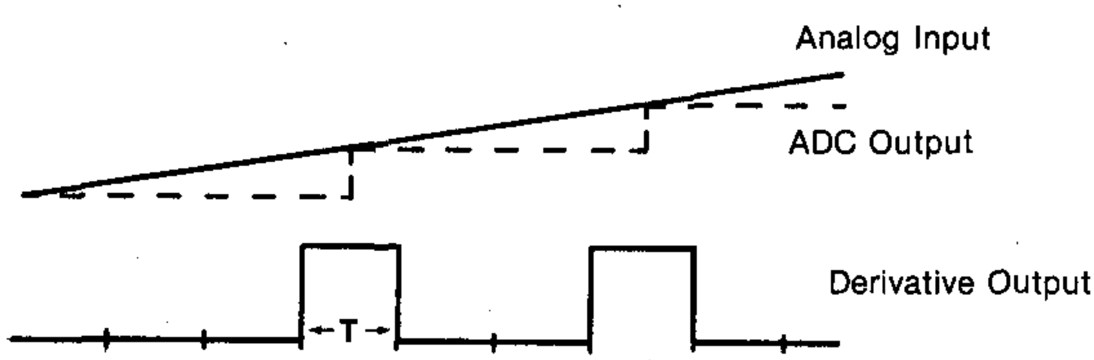

Figure 6: Discretization Error.

At the point at which the threshold is exceeded, the input changes by one bit and the derivative assumes a rate of change of one bit per sample. At the next sample instant no change occurs and the derivative returns to zero. The resultant pulsations in the valve are undesirable and for this reason derivative action is seldom used.

Advantages of Digital Control

The two main advantages of digital control are its flexibility and its ability to handle slow process. Flexibility means that almost any algorithm can be used and changed until the best results are obtained.

The ability to handle slow processes is an after overlooked advantage. For example, integral times of between 60 and 120 minutes, impractical to obtain with analog controllers, can be obtained by simply increasing the sampling time to 10 to 20 minutes.

Sampling Rate

The ADC converts the analog signal to a digital number which represents the analog process only at the instant of sampling. If the process is sampled too slowly the digital value will not accurately represent the analog process. (Figure 7)

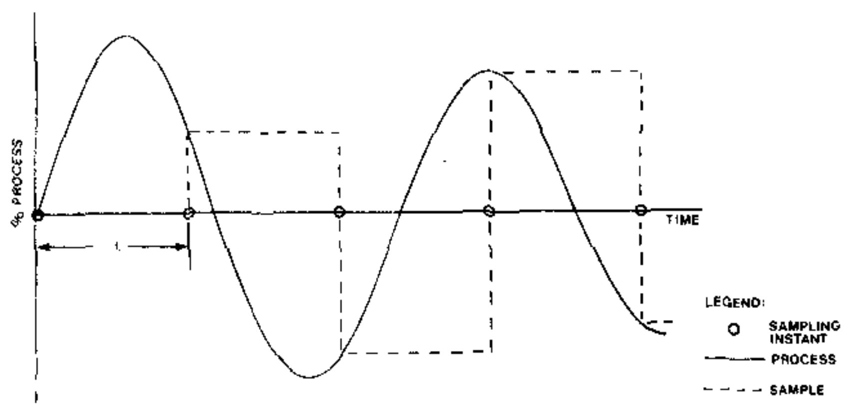

Figure 7: Effect on Digital Signal Quality When Sampling Rate Too Low.

Obviously, the faster a process responds, the faster the digital sampling rate must be. To determine a valid sample time (time between each sample) the cyclic period of the process should be known. In theory the sampling rate theorem states that for a signal of frequency 'f' all the information will be eventually retrieved if the sampling is at a frequency of '2f'.

In practice the sampling rate is set to 8 to 10 times the process frequency. The faster the sampling rate, the better the analog signal is represented at the ADC output (Figure 8). Sampling at a very fast rate would obviously produce near perfect measurement results. However, all of the computer time would be dedicated to sampling the same quantity with very little advantage in return.

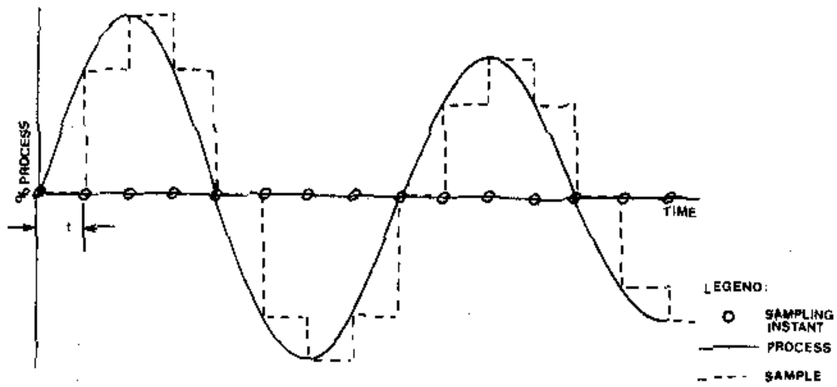

Figure 8: Digital Output With Faster Sampling Rate.

In practice, typical sampling periods for the Digital Control Computer (DCC) system in Candu stations are in the order of 0.5 to 50 seconds. This period will adequately reproduce the signal.

ASSIGNMENT

1. Present a block diagram representing the level control of five open tanks.

2. State the function of the following items of equipment:

   (a) Multiplexer
   (b) Sample and Hold
   (c) Analog to Digital Converter
   (d) Digital to Analog Converter

3. An analog temperature transmitter has a resolution of 0.5%, what is the minimum number of bits an ADC must have to preserve this resolution.

4. Show how the digital integral and derivative function may be obtained from an analog signal sampled at time interval T.

5. Discuss aliasing error, how is it caused and how can it be cured?

6. Describe how a digitally controlled process can introduce dead time into a control loop. How can this dead time be decreased?

7. Explain how derivative action in a digitally controlled process can cause unwanted pulsing of the final control element.

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