

DIGITAL CONTROL SYSTEMS : A CASE STUDY

This example was presented at the AUTOMATION 77 conference in Auckland. That makes it fairly old, but it's a very good worked example, and the control theory used here hasn't changed.

It has been converted from the original typescript by scanner (which introduced a number of errors) and me (which removed a lot more, but could also have inserted some new ones – in some places, the wording of the original was obscure, and I've replaced it with my best guess at the intended meaning). I have also added some annotation in Helvetica font.

**DIGITAL CONTROL OF A THREE TANK LEVEL SYSTEM –
A CONTROL SYSTEM USED FOR TEACHING COMPUTER CONTROL.**

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SUMMARY

The system consists of water being supplied from a constant head tank via a control valve to three non-interacting tanks. The control valve throttles the flow into the first tank, which discharges through a fixed orifice into a second tank of the same dimensions which discharges through a fixed orifice into a third tank of the same dimensions which discharges through a fixed orifice to drain. The level in the third tank is measured and this signal is transmitted to a Nova minicomputer, which compares the measured level with a desired level and then computes an output signal that modulates the control valve opening.

The system has been fully analysed and its operation simulated using linear and non-linear models to predict optimum controller settings, and the system has in fact been operated using conventional analog (Pneumatic) control. The main emphases of the computer control study investigated have been the choice of the three-term control algorithms, the variation of gain to compensate for the non-linearity of the control valve and the possibility of including an algorithm to make the system self-tuning.

System description

The system chosen for this control study was a level-control system containing three tanks, mounted vertically above one another. Figure 1 is a schematic diagram showing the main elements of the system. The water supply to the top tank, number 1, came from a header tank, thus eliminating the influence of uncontrolled water pressure fluctuations on the system. Tank 1 discharged into tank 2 and tank 2 into tank 3. The effluent from tank 3 is discharged to drain. The tanks were all of the same dimensions and their outflow

resistances were three orifice plates of identical orifice size, thus ensuring that the time constants associated with the linear models of these elements were identical. The system variable chosen to be controlled was the level in tank 3 and the manipulated variable was the flow into tank 1. Two system disturbances were chosen, set point and load changes. Set point changes were effected at the controller. The load disturbance was achieved by having a second line from the header tank discharge an uncontrolled (by the controller) preset flow into tank 1. The control action was achieved by one of two alternative schemes. Conventional analog control was made possible by measuring the level in tank 3 with a pneumatic differential pressure transmitter. The 20 to 100 kPa output signal was transmitted to a model 52A Foxboro pneumatic three-term controller and the output from the controller sent to the control valve. The second control scheme involved taking the output of the pneumatic differential pressure cell, converting this to a 2 to 10 Volt signal that was transmitted to a Data General "Nova" minicomputer, via a Fairchild analog-to-digital converter. The control action was then generated within the computer, using the chosen control algorithm and a signal sent, via the digital-to-analog converter, to a transducer that converted the 0 to 10 Volt signal to 20 to 100 kPa signal that went to the control valve. The Data General "Nova" minicomputer had 12K of core memory and the analog-to-digital (A/D) and digital-to-analog (D/A) converter had 8 A/D channels and 4 D/A channels.

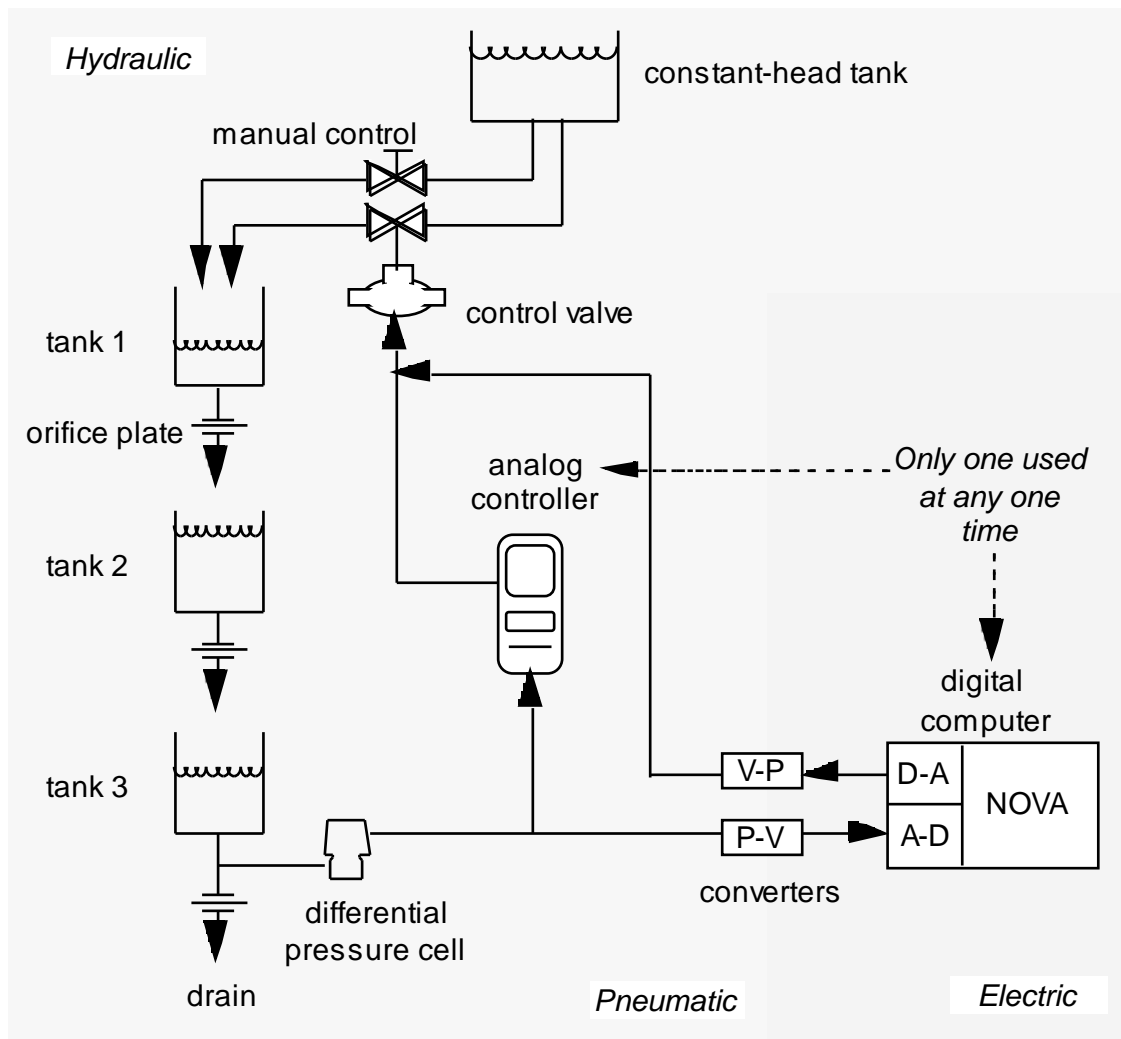


FIGURE 1 Three-tank level system

System analysis

First step : analyse the ideal system.

The three-tank non-interacting level control system was considered to be ideal for the development of this model. From the continuity of flow equation, the following equations for the system, Figure 2, were derived;

$$(q_1 + I) - q_2 = A \, dh_1/dt \quad (1)$$

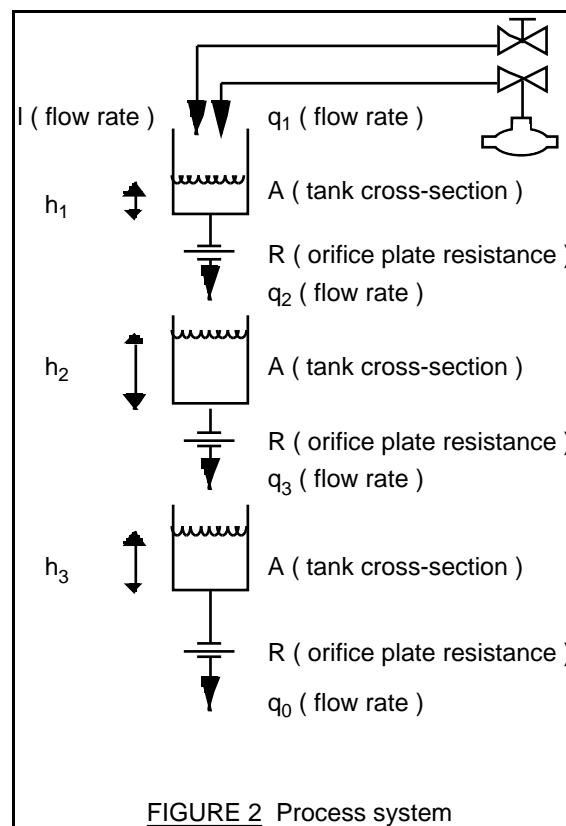
$$h_1 = R \, q_2 \quad (2)$$

$$q_2 - q_3 = A \, dh_2/dt \quad (3)$$

$$h_2 = R \, q_3 \quad (4)$$

$$q_3 - q_0 = A \, dh_3/dt \quad (5)$$

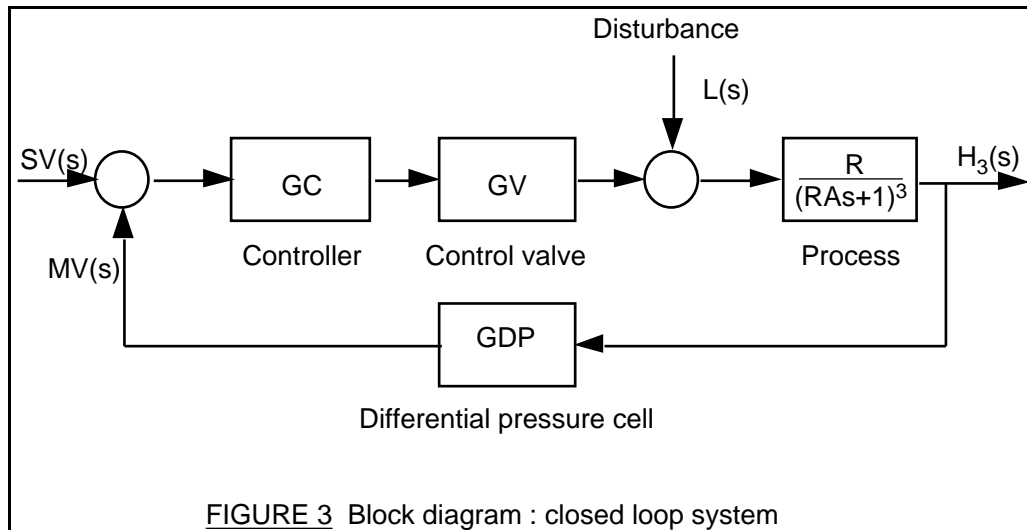
$$h_3 = R \, q_0 \quad (6)$$



These equations are transformed and combined to give a process transfer function of :

$$\frac{H_3(s)}{Q_1(s) + L(s)} = \frac{R}{(RA s + 1)^3} \quad (7)$$

If the control loop is closed around the process, it can be represented by the block diagram of Figure 3.



Now introduce the real system.

The control valve in the system is a Kieley and Mueller type 1250R single seated valve, fitted with a $\frac{1}{2}$ inch linear 'Formflo' plug. At this stage, the control valve is assumed to have the inherent characteristics of the plug and to be linear. A model of the valve will be discussed later in this paper.

An assumption of linearity has been made; now test it..

A program was written in Basic with Calls to simulate the open-loop system and a unit step change was made to the input of the system and the output was recorded and compared with the open-loop response obtained during analog testing of the system. The results from both systems are shown on Figure 4. The model provides a reasonable match with the experimental open-loop response. The most significant discrepancy is in the first one third of the response and is due to the system non-linearities.

FIGURE 4 Open-loop response

Analyse the test results.

The principle non-linearities which have been considered are as follows in approximate decreasing order of deviation from linearity :

1. Control valve and pipe line
2. Orifice plate
3. Vortex effect
4. Controller

1. Control valve non-linearities.

The non-linearities experienced in the test carried out were too large to be explained by the normal square root law orifice non-linearities. The valve characteristic including the effect of the line pressure drops were measured. The flow vs. control pressure characteristic is shown plotted in Figure 5. It can be seen from the graph that the valve characteristic cannot be represented by a simple power law.

Figure 5

2. Orifice non-linearities.

The type of non-linearity expected with the three-tank process is due to the orifice plate characteristic.

It should be noted that the process time constant will change with operating point due to variation in slope of the orifice characteristic. (So there's still an assumption of linearity.)

3. Vortex effect.

The vortex effect was noticed when the levels fell to within a few centimetres of the bottom of the tank. A vortex was formed and, while the level still oscillated, the centre of the surface was significantly depressed and gradually formed a deeper and deeper depression. This caused a significant drift down of the mean level of the measured value taking it below the expected final value.

4. Controller non-linearities.

Controller non-linearities were not expected to be of significance. Section 6.6 of Reference 6 discusses controller non-linearities. Errors of 10 to 50% in integral and derivative time settings were found as well as changes with absolute pressure and direction of step. Also, major errors in gain calibration and linearity were discovered.

These non-linearities are the reason why analog control of the process works only for a limited set point range and better control response of the system should be expected from direct digital control of the system.

Non-Linear model.

A non-linear model of the control valve was generated using a Basic program that fitted the valve characteristic to a n th order polynomial equation. This model also included a square root approximation of the orifice/tank non-linearity. This non-linear model of the control valve and orifice/tank characteristic was written into the open-loop process model. A set change was made to the input of the system and the output was measured. The results obtained from the non-linear model provided a very close match with the experimental open-loop response.

Now test the control systems.

Analog control

The analog controller was connected into the process in parallel with the digital computer as shown in Figure 1. The open-loop response of the analog system was tested by applying a step change to the output of the controller while in the manual control mode. The open-loop response for the system is shown in Figure 6. From this open-loop response, the Ziegler and Nichols "optimum" settings by the process reaction curve method were calculated (Reference 7). The values calculated were :

Proportional Band,	$P_b = 17.5\%$
Integral Time,	$T_i = 9.88 \text{ mins.}$
Derivative Time,	$T_d = 0.22 \text{ mins.}$

These optimum settings were set on the controller and the system was allowed to reach its steady state and it was then transferred to auto control. The set point was then pulsed by 10% and the system response was recorded. The control obtained was far from optimal so the control was then timed using the method as laid out in Reference 1. The optimum settings obtained by this on-line tuning method were compared with those obtained by Ziegler and Nichols method. The only significant difference appeared to be the proportional band actually set on the controller to that obtained by calculation. At this point, the proportional band of the controller was checked to obtain some idea of the actual value of the proportional band to the value of the proportional band set on the controller. The result of this test is plotted in Figure 7. It can be seen that the proportional band unit is non-linear and there is a discrepancy in the value set to the actual value. With this knowledge, the proportional band setting obtained by Ziegler and Nichols methods was corrected and the test carried out again.

FIGURE 6 Open loop response of the system.

Figure 7

These corrected settings were applied to the controller and the test carried out again. From the results obtained, Figure 8, it could be seen that these settings gave optimum control for that flow setting provided that the level was maintained within 21-35% of the range. This is within the linear region of the valve.

Figure 8

DIGITAL CONTROL

Program description

The program's overall block diagram is shown in Figure 9. The program was written in the Basic language with calls to a set of assembler level subroutines. This allows real-time programming from Basic and also analog-to-digital and digital-to-analog conversions. All the information required from the operator to run the system is requested by the teletypewriter. Thus the program interacts with the operator.

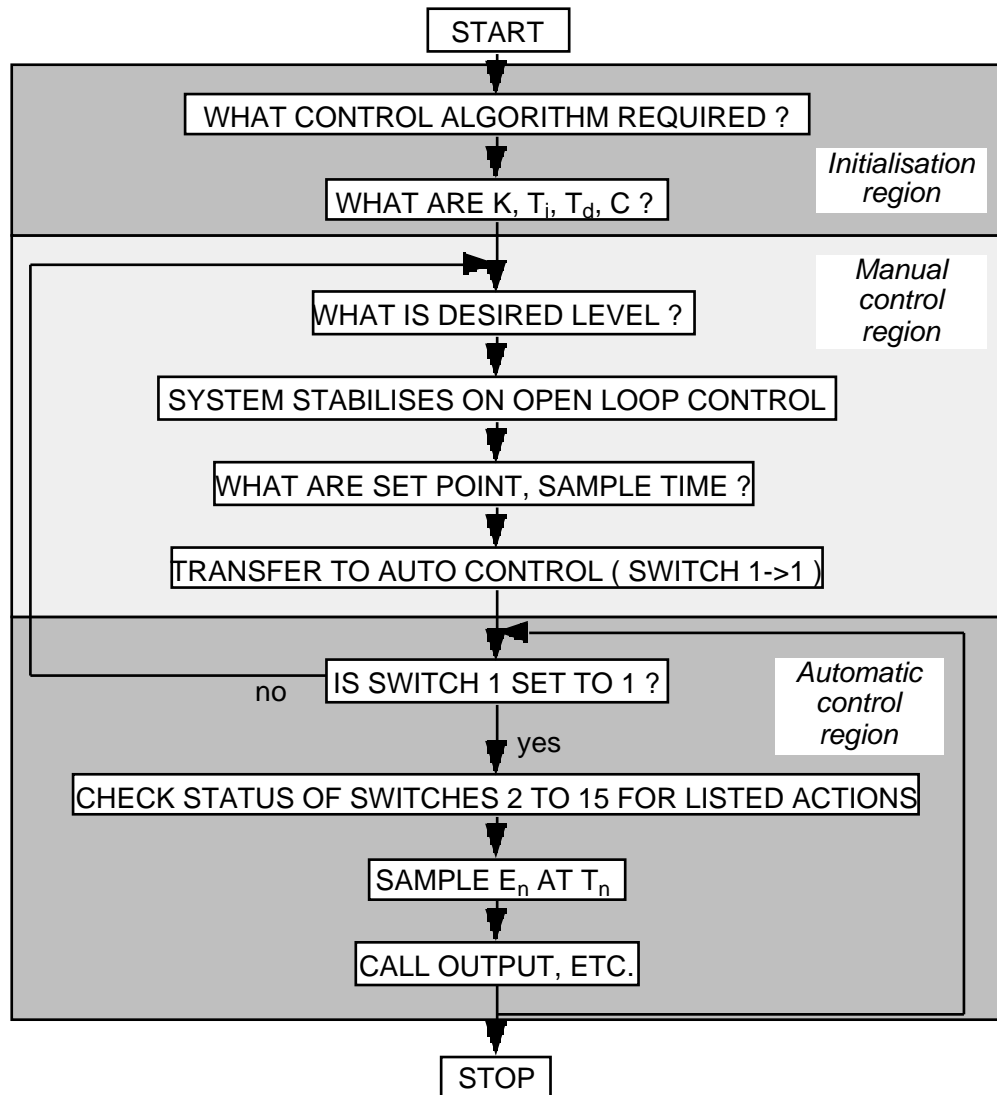


FIGURE 9 Computer program block diagram

(I don't believe the STOP; there should be a decision box there somewhere. But that's what it said.)

The structure of the program is as follows. There are three main sections in the program : Initialisation, Manual Control Operation and Automatic Control Operation.

- During *Initialisation*, the following are requested :
 1. The selected controller algorithm. This will be discussed in a later section of the paper.
 2. The initial controller parameters : proportional band, integral time, derivative time and derivative gain factor.
- In the *manual control* section, the desired level is requested. After the desired level is entered, the computer sets the system to open-loop control configuration and no further action is invited from the operator until the measured value is within $\pm 10\%$ of the desired level. (Note the special starting-up sequence.) The set point and the sampling time are then requested by the teletypewriter. The program then proceeds to the automatic control configuration when the status of console switch 0 is set to 1.

- In the *automatic control* section, the program executes the following tasks :
 1. The console switches are scanned and for those whose status is 1 the call program for that task is executed. These call programs will be discussed at a later section of the paper.
 2. The measured value is compared with the set value and an error value E_n is produced at that time T_n .
 3. An output is calculated, using the selected controller algorithm, which is related to the error so as to reduce the error to zero.
 4. The output signal is transferred to the control valve via the digital-to-analog converter.
 5. The program transfers control back to task 1.

One of the console switches is used to transfer the system from automatic operation to manual control (switch 1) and another (switch 15) is used to terminate the experiment. Note, new values of P_b , T_i , T_d and T can be supplied during the automatic operation section and the set point can be stepped up or down by 10% using switches 6 or 7.

Calls

When on automatic control, the following functions may be called by setting the status of the specified console switch to 1.

- Switch 1 : Transfers the system from automatic control to manual control.
- Switch 2 : Parallel type control algorithm, non-interaction between modes.
- Switch 3 : Parallel type control algorithm, non-interaction between modes, derivative gain limited.
- Switch 4 : Series type control algorithm, interaction between modes, derivative gain limited.
- Switch 5 : Parallel type control algorithm, non-interaction between modes, no derivative action on set point changes.
- Switch 6 : Increases the set point value by 10% each sample interval.
- Switch 7 : Decreases the set point value by 10% each sample interval.
- Switch 8 : Control valve compensator – linear characteristic.
- Switch 9 : Control valve compensator – equal percentage characteristic.
- Switch 10 : Evaluation of IAE.
- Switch 11 : Print value of IAE.
- Switch 12 : Input values of : P_b , T_i , T_d , T and initialised IAE.
- Switch 14 : Print the value of the set point, measured value and controller output signal.
- Switch 15 : Stop.

To remove the call, set the status of the specified console switch to 0.

Controller algorithms

The basic controller algorithm of a direct digital computer control system is one which replaces the control action performed by the analog controller of a conventional control system. In analog controllers, the control modes are connected in a series or parallel arrangement. The controller mode settings interact in the series-connected form and are non-interacting in the parallel-connected form.

Form 1 : A typical continuous proportional-plus-integral-plus-derivative controller. It may be described by the transfer function shown in equation 8.

$$P_o(s) = K (1 + 1/T_i s + T_d s) E(s) \quad (8)$$

This is a parallel-connected controller, Figure 10 is the block diagram.

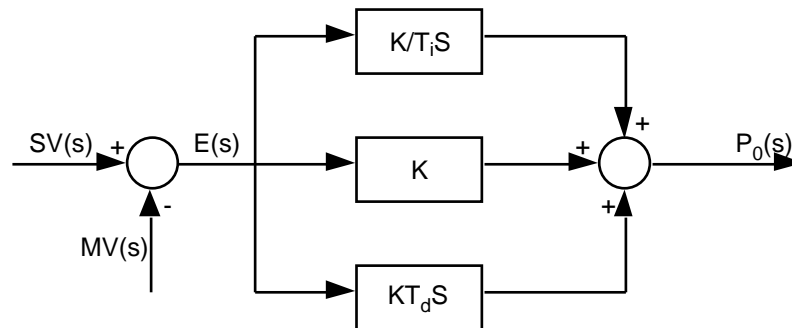


FIGURE 10 Parallel connected controller modes

Form 2 : This is the series-connected form, represented by Equation 9 and Figure 11.

$$P_o(s) = K (1 + 1/T_i s) (1 + T_d s) E(s) \quad (9)$$

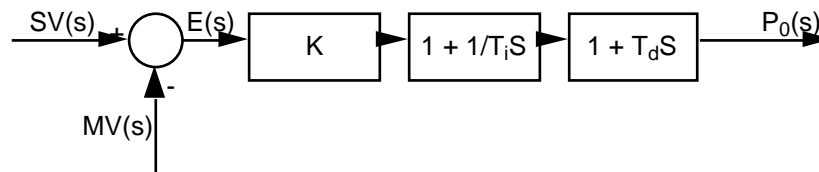


FIGURE 11 Series connected controller modes

Form 3 : The working form of the equation, describing the three-term series-connected type controller, equation 10, differs slightly from equation (9) by the addition of a factor, $(1 + (T_d/G) s)$, which provides derivative gain limiting. The constant G is the derivative gain limiter.

$$P_o(s) = K (1 + 1/T_i s) ((1 + T_d s) / (1 + (T_d/G) s)) E(s) \quad (10)$$

Form 4 : The form of the equation describing the three-term parallel-connected controller whose modes have been arranged to avoid derivative action on set point changes :

$$P_o(s) = K (1 + 1/T_i s) E(s) + K T_d s MV(s) \quad (11)$$

This is the transfer function for the parallel connected type, with no derivative action on set point changes, Figure 12.

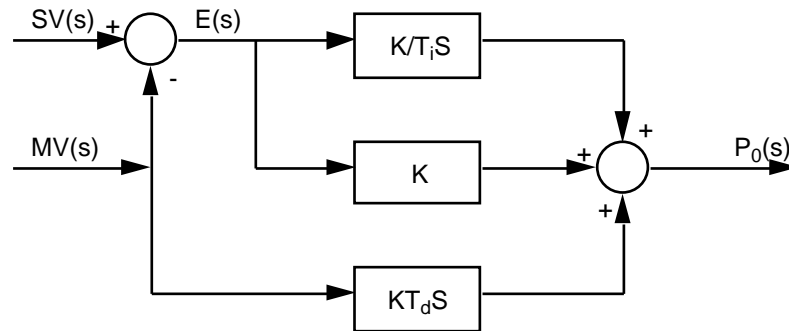


FIGURE 12 Parallel connected, no derivative action on set point changes.

The continuous control equations are expressed in discrete form – specifically, in the digital control algorithms, in the positional form. The positional form of the equation is such that during the n th sample period, the computer calculates the desired position of the manipulated variable and not the change in position. The reason for the selection of the positional form is that, in direct digital control, all three control modes are potential suppliers of controller "windup". Controller "windup" occurs when the final control element of the control loop has saturated at a fully open or closed position. In general the type of "windup" depends on the form of the discrete control equation. When the change in position form is used, proportional and derivative windup can occur; when the positional form is used, integral windup can be easily contained without introducing other problems, hence the positional form of the discrete control equations was used.

Four discrete controller algorithms were written into the program and may be selected by setting the status of the appropriate console switch to 1. The algorithms available and their discrete equations are :

Algorithm 1 (Switch 2). Parallel type, non-interaction between modes.

$$P_o = P_n + I_n + D_n \quad (12)$$

where

$$P_n = K E_n \quad (13)$$

$$I_n = I_{n-1} + K I E_n T \quad (14)$$

$$D_n = K 2 (E_n - E_{n-1}) / T \quad (15)$$

Algorithm 2 (Switch 3). Parallel type, non-interacting, derivative limited.

$$P_o = P_n + I_n + D_n \quad (16)$$

where

$$P_n = K E_n \quad (17)$$

$$I_n = I_{n-1} + K I E_n T \quad (18)$$

$$D_n = A (1 - B) (E_n - E_{n-1}) + B D I \quad (19)$$

Algorithm 3 (Switch 4). Series type, interaction between modes, derivative limited. (Note that these equations are exactly the same as those for Algorithm 2. That's how it is in the original. I know it's wrong, but haven't had time to sort out which is which.)

$$P_o = P_n + I_n + D_n \quad (20)$$

where

$$P_n = K E_n \quad (21)$$

$$I_n = I_{n-1} + K1 E_n T \quad (22)$$

$$D_n = A (1 - B) (E_n - E_{n-1}) + B D1 \quad (23)$$

Algorithm 4 (Switch 5). Parallel type, non-interacting, no derivative action on set point changes.

$$P_o = P_n + I_n + D_n \quad (24)$$

where

$$P_n = K E_n \quad (25)$$

$$I_n = I_{n-1} + K1 E_n T \quad (26)$$

$$D_n = K2 (M_n - M_{n-1}) / T \quad (27)$$

Tuning the algorithm

The critical phase of the implementation of the control algorithm is the selection of the numerical values of the constants in the control algorithm. The open-loop method of Ziegler and Nichols was used to obtain the open-loop response data, because of the ease with which the necessary experimental data can be obtained. From the open-loop response data, the numerical values of the controller settings were obtained. This was found to give values of K, K1 and K2 close to the optimum set. G was set at 10 when used. This optimum value of G was determined during frequency and step response tests on the controller algorithms.

Optimisation of the controller algorithm setting was carried out using an error-integral criterion. The integral of the absolute value of the error (IAE) criterion was used since the criterion is based on the whole response and is more sensitive to small errors but less sensitive to large errors; this tends to give a time response that is less oscillatory than quarter decay ratio, which is another criterion that has been used in the process control industry as a reasonable trade off between a fast rise time and a reasonable settling time.

A call, initiated by setting the status of switch 10 to 1, was written into the program to calculate the value of the IAE and print the value of the IAE at the completion of the test.

The operator has to be able to change or trim the control mode setting while the system is on automatic control. If the status of switch 12 is set to 1, new values for proportional band, integral time, derivative time, sample time and the derivative gain factor may be introduced into the control algorithm, and IAE is set to zero.

Sample time

The control sampling time can be changed while the system is on automatic control. This allows the operator to observe the effect on the control response with change in sample time. The choice of the sampling time becomes a matter of choosing the maximum time consistent with effective control so as to reduce the computational load on the computer. Three methods for selecting the sample time are given in detail in reference 3. The three methods for selecting the sample period are outlined in order of increasing accuracy and complexity.

1. The loops are simply categorized according to the type of controlled variable involved. Flow loops are sampled at 1 second intervals; level and pressure at 5 second intervals; and temperature and composition at 20 second intervals.

2. The control sample period can be related to the integral time constant for proportional plus integral control and to the derivative time constant for proportional plus integral plus derivative control.
3. When the process dynamics are known then the control sample period can be related to the process dead time and the sum of the process time constants.

It was decided to further investigate the relationship between the natural period of the process, T_n , and the sample time, T .

The effect of varying the sample time, T , are shown in Figures 13, 14 and 15. In these experiments, the sample time was progressively increased from 2.13 secs. (Figure 15), which is one sixteenth of the system natural period, to 8.5 secs. which is one quarter of the natural period. Everything else was left constant. As can be seen by comparing these graphs, the system performance deteriorated slightly between $T = T_n/16$ and $T = T_n/8$. The deterioration was much more pronounced between $T = T_n/8$ and $T = T_n/4$. Thus it would seem that T should be left below $T_n/10$ to eliminate this type of deterioration of the control system performance.

Control valve compensator

In the selection of control valves, consideration should be given to keeping the product gain and the value constant throughout the range of the control valve. This increases the likelihood that the overall system behaviour will be linear and that a set of controller parameters will be adequate for all levels of system operation over the full range of the set points that fall within the operating range of the system. Thus, for a linear process, a valve with a linear characteristic would be selected. If the process becomes less sensitive to the throttled stream as the load increases, a valve whose gain increases with opening is required. This is the characteristic of an equal percentage or parabolic valve. If the reverse is the case, a valve with a decreasing gain-opening relationship is required.

To simulate the effects of changing the type of control valve, two algorithms were prepared. In one, the relationship between the controller output and the valve action that resulted was changed to simulate the effects that would be obtained using a linear valve. In a second algorithm, this relationship was changed to yield valve action equivalent to an equal percentage valve. Thus three types of valve could now be tried : the original valve characteristic, as shown in Figure 5; a linear characteristic; and an equal percentage characteristic.

On comparing the system performance with those types of valve, the following results were observed. The original valve with digital control performed only marginally better than analog control. Specifically, if the system was operated with the set of proportional band, integral and derivative time values that were optimal at a setpoint set at 30%, it became uncontrollable when the set point was shifted beyond 50%. With the linear valve algorithm included, the overall performance improved such that the set point could be changed to 50% and the system was still stable. The system became unstable when the set point was moved beyond 70%. With the equal percentage algorithm, the best performance was obtained. This is discussed in the following section.

Optimal digital control

Figure 16 shows the system response to a load change (at set point of 20%) using the equal percentage control valve algorithm and a subsequent set point change from 20% to 80%. These disturbances are considered to be extreme, and the system under analog control would not have coped with them. In particular, the extreme set point change (20% to 80%) used in this test would have resulted in unstable performance with analog control. The direct digital control system on the other hand responded satisfactorily in both cases, the effects of these disturbances having died after two oscillations. This demonstrates the superiority of the direct digital control system over the analog system.

Figure 16

Self-tuning algorithm

The final part of this project was to investigate the prospect of having a self-tuning control algorithm included into the system as a call. The direct digital control computer can be readily used to test the plant dynamics and tune the parameters of the control algorithm.

When on automatic control, the self-tuning algorithm could be called by setting the status of switch 13 to 1. Once the algorithm has been selected, the computer waits for the process to reach steady state conditions. The computer could then :

1. Internally disconnect the feedback making the process open-loop.
2. Pulse the output signal to the valve so as to introduce a 10% step change into the process.

3. Measure and record the open-loop response of the process.
4. Calculate the optimum controller settings using Ziegler and Nichols criteria or, if the normal Ziegler and Nichols formulae were thought to be unsuitable for the particular process under consideration, modified Ziegler and Nichols formulae.
5. Pulse the output signal with a 10% step back to the original output level and calculate a second set of controller settings. The mean of the two groups of settings is then calculated for subsequent use.
6. Internally reconnect the process to the closed-loop condition and transfer the controller settings to the controller algorithm.
7. Return the system to automatic control under the main program.

At the time of writing this paper, the call program was in the developmental stage hence results or conclusions resulting from the use of the self-tuning algorithm were not able to be presented.

CONCLUSIONS

As a result of this study, the following conclusions were reached.

The analog system, as originally assembled was limited in its performance by several factors. The vortex effect experienced in measuring low tank levels made the system uncontrollable below 10% of the total tank height. When the system was adjusted with the optimum settings at a set point of 30%, the range of controllability was for set points between 10% and 50%. The system also could not cope with large load disturbances as these had the effect of causing a shift to a different part of the control valve characteristic, thus changing the valve gain and requiring a new controller gain for optimal performance.

The digital controlled system was a marked improvement. A range of controller algorithms was available simply by setting different switches and a range of control valve characteristics by similar switch selection. Thus, using a three-term parallel mode controller with limited derivative gain and an equal percentage value algorithm, step changes of the set point from 20% to 80% could be tolerated.

The digital control system was found to be easier to operate than the analog system and could be easily adapted to different strategies by minor modifications or extensions to the software. The addition of the self-tuning algorithm in particular would minimise or perhaps even eliminate the work involved in establishing the optimum controller characteristics.

The programming strategy adopted was quite successful and could be adapted to serve other single input, single output systems or even multi-input multi-output systems. This will be attempted in future studies.

Nomenclature

A	The ratio of the integral time constant to the sample time (T_i/T).
A_t	Tank cross-sectional area (m^2)
B	$1/(1 + (T * G/T^2))$
D_n	Calculated derivative action, n th sample period.
E_n	Control error, n th sample period.
f	Frequency (Hz)
G	Derivative gain factor.

h_1, h_2, h_3	Liquid levels in tanks (m).
I_n	Calculated integral action, n th sample period.
IAE	Integral of the absolute error.
ISE	Integral of the square error.
ITAE	Integral of the time multiplied by the absolute error.
K	Proportional gain.
K_I	Integral gain (K/T_i).
K_D	Derivative gain ($K * T_d$).
l	"Uncontrolled" flow rate into tank 1 (m^3/s).
$L(s)$	Transformed form of l ($L(s) = L(l)$)
M_n	Measured value, n th sample period.
mv	Measured value, input to controller.
$MV(s)$	Transformed form of mv ($MV(s) = L(mv)$).
P_n	Calculated proportional action, n th sample period.
P_b	Proportional Band.
PID	Proportional, integral and derivative.
P_n	Calculated control output.
q_1, q_2, q_3, q_0	Flow rates into or out of tanks (m^3/s).
$Q1(s), Q0(s)$	Transformed form of q_1, q_0 ($Q1(s) = L(q_1)$)
R	Tank discharge orifice plate resistance (s/m^3).
s	Laplace variable.
sv	Set value, input to controller
$SV(s)$	Transformed form of sv ($SV(s) = L(sv)$)
T	Control sample period (mins).
T_d	Derivative time constant (mins).
T_i	Integral time constant (mins).
T_n	Natural period of process (mins).

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