METERIALS AND METHOD

Materials

Hardware

1. Source tank.
2. 38.5 cm. ID tanks.
3. PVC pipe ID ¾”.
4. Globe valves.
5. Electric wire.
6. Air tube.
7. Yokogawa YS150 controller.
8. Yokogawa EJA110 Differential pressure transmitter.
9. Sigma SFN48-M-RRA-N controller.
10. Nagano ADZ-SMX-10.0 pressure transmitter.
11. Thermocouple type K.
12. Yokogawa Valtek Control valve.
13. Flange heater 3,000 W.
14. Hitachi Magnetic contactor.
15. Eurogear centrifugal pump.
16. Fuji MINI Inverter.
17. PUMA Air-compressor.
18. Personal Computer.
    - 18.1 CPU (Intel(R) Pentium(R) D CPU 3.40 GHz (2CPUs))
    - 18.2 1.00 GB of RAM
    - 18.3 240 GB of hard disk
19. Signal Conditioning eXtensions for Instrumentation.
    - 19.1 SCXI-1122
    - 19.2 SCXI-1124
    - 19.3 SCXI-1322
    - 19.4 SCXI-1325
    - 19.5 SCXI-1000
20. National Instrument Data Acquisition Card E-6024 (DAQ card).
21. Wisco Analog signal splitter.

Software

1. Microsoft Windows XP Professional Version 2002 Service Pack 2.
2. Measurement and Automation eXplorer 4.0 (MAX).
3. Software LabVIEW 8.0.
4. Internet Explorer 7.0.

Methods

This work designed one tank and two-interacting tank processes in order to control on web-based by using LabVIEW. In order to control, this system which consists of a heater and stirrer is chosen here as a case study. The simple diagram of this system is shown in Figure 2. It is assumed that the properties of fluid are constantly throughout the tank system. The fluid from the source tank is forced by pump to flow to tank 1. Level is indicated by differential pressure transmitter and manipulated by the first control valve (CV1). Thermocouple measures temperature in the heating tank.

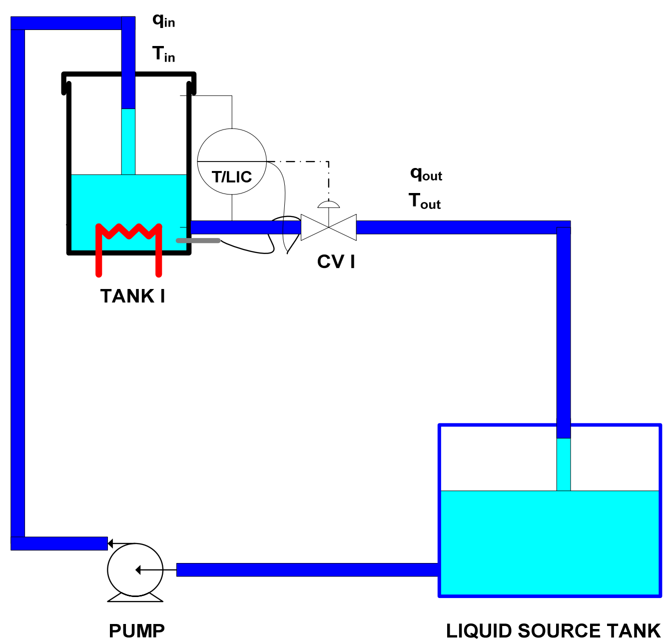


Figure 2 One circulated tank system

It is well known that one tank system is a basically control thus the interacting is very interesting for the next study. Two-interacting tank is designed for control the interacting process. The two-interacting tank system can be modified as shown in Figure 3. From Figure 2, the second identical size tank is coupled together with the first tank. Then, the outflow of second tank is manipulated by the second control valve (CV2).

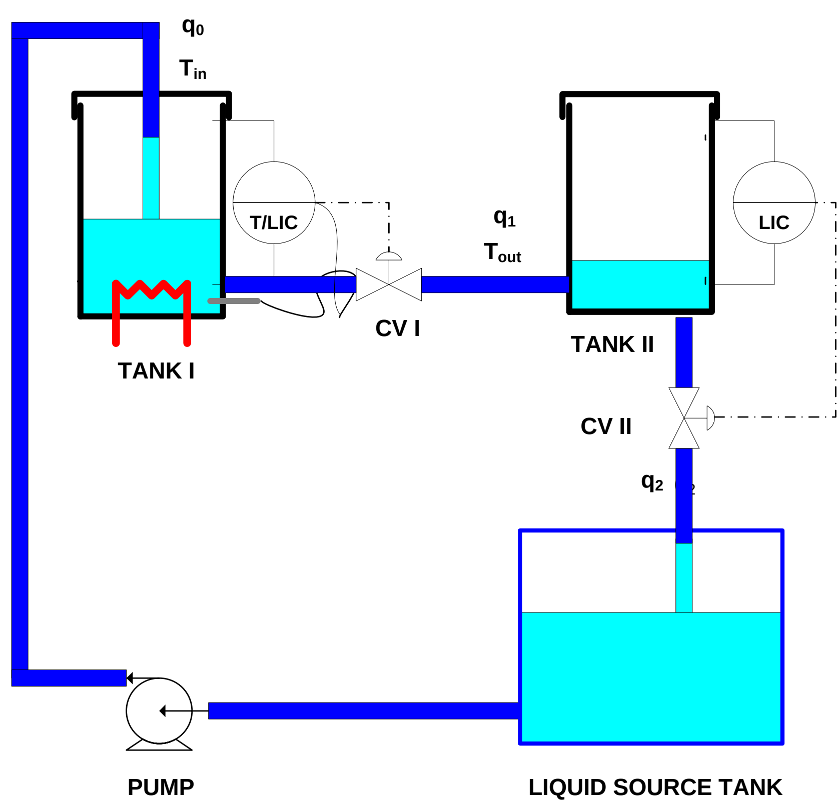


Figure 3 Two interacting tanks system

This research will focus on setting up the control system to control the two-interacting tank process. And this process is developed by using the GUI for control online via the internet. The steps of work in this research are following:

1. To set up the control system for two-interacting tank process.
2. To generate mathematical model for proposed systems.
3. To design the various controllers, PID, IMC, GMC, and FLC

1. <u>To set up the control system for two-interacting tank process.</u>

The two-interacting tank system is set up by six groups of equipment as follow

- Computer
- Basic equipment
- Utility Hardware
- Signal conditioning
- Final control element
- Sensor and/or transmitter

This equipment is necessary for this work. The details of this equipment are in the APPENDIX A.

The operation of this process can be described as follow. Firstly, the two identical size tanks are connected together and they are placed over the liquid source tank. Then, the liquid was only fed into the first tank while the liquid in the first tank was heated by heater. After that, the hot liquid from the first tank flowed into the bottom of the second tank. Finally, the liquid from the second tank flowed back the source tank. This process used 4-20 mA analog signals to communicate with signal conditioning box. This box was connected with data acquisition card in order to convert the analog to digital signal and *vice versa*. SCXI-1322 obtained the 4-20 mA analog signal from sensor and/or transmitter and SCXI-1325 sent the 4-20 mA analog signal to the final control element. The level of tanks was measured by differential pressure transmitters, which the signal is 4-20 mA. The temperature in the first tank was measured by thermocouple type K, which the signal is degree Celsius. For convenient in control, degree Celsius unit is converted to the 4-20 mA form by analog signal splitter of Wisco. The sensors and/or transmitters must be calibrated in order to obtain the correct controlled values for control. Feedback control is used in this control. This process is shown in Figures 4 and 5. In Figure 4, the left down tank is not used in this work. Computer aid control is used in this work therefore it is added in to Figure 5.

Figure 4 Two-interacting tank process

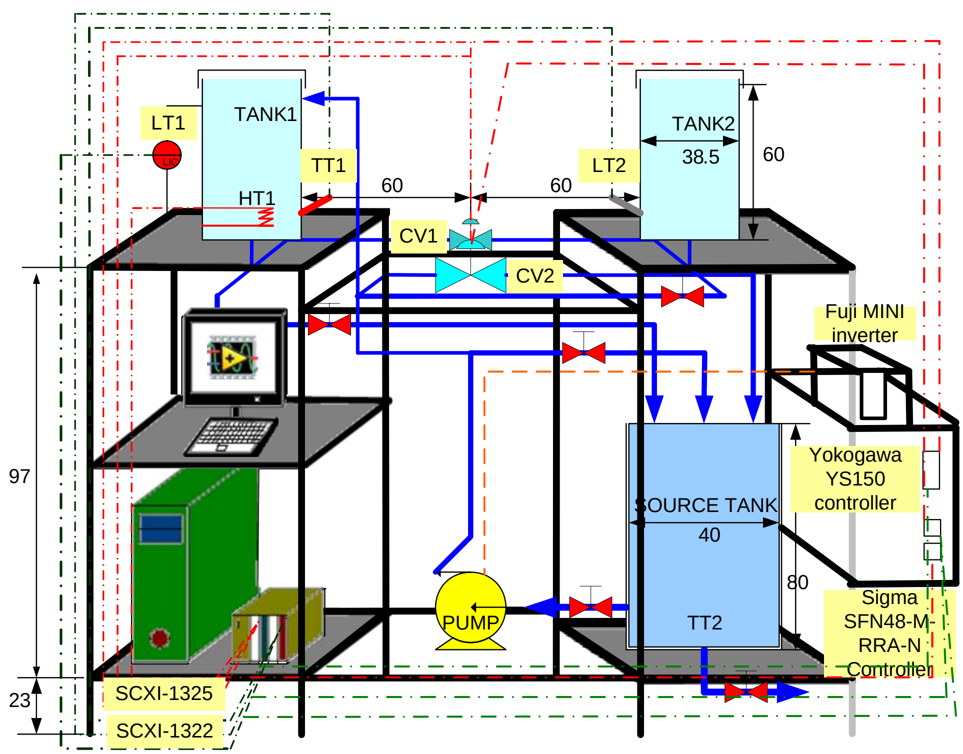


Figure 5 Two-interacting tank diagram

LabVIEW 8.0 is used for application to control system and MAX 4.0 is a driver of signal conditioning. The conclusion of the signal conditioning connection and sensor and/or transmitter and final control element are shown in Table 1.

Table 1 Connection signal conditioning terminal with equipment

SCXI-1322		SCXI-1325	
Channel	Sensor/Transducer	Channel	Final control element
1	LT1	1	CV1
2	LT2	2	CV2
3	TT1	3	HT1
4	TT2	4	Inverter

2. To generate mathematical model for one tank and two-interacting tank.

A process has a "tank capacity" to store material or energy and some factor which resists the storage of additional energy or material. This resistance has the effect of limitation in the change and causes the process to be "self-regulating". This process is called "pure first order process".

Figure 2 illustrates the first order process. The outflow (q_{out}) is no longer constant, but now is proportional to the fluid head in the tank. The tank represents the capacity to store material and the outlet valve is the element which resists a change in fluid level. With the increased fluid level, the pressure at the bottom of the tank increases. The fluid level will continue to rise until the increased pressure at the bottom of tank makes inflow (q_{in}) equal to the outflow (q_{out}).

A liquid flow in a tank at temperature T_{in} is available at a constant flow rate of q_{in} in units of mass per time. It is designed to heat this liquid to a higher temperature T_{out}. The proposed heating system is equipped with a heating device; flange submerge heater. The operating conditions are T_{outsp} for temperature and h_{sp} for level.

2.1 Mass balance

Accumulate rate of mass in the tank = Mass flow rate in – Mass flow rate out

$$\rho A \frac{dh}{dt} = \dot{m}_{in} - \dot{m}_{out} \qquad (1)$$

Where $\dot{m}$ = mass flow rate (kg/min)

ρ = density of liquid (kg/m^3)

A = cross section area of tank (m^2)

h = level of liquid in tank (m)

t = elapsed time (min)

ρ constant is assumed, in terms of the variables used in this analysis, the mass balance becomes:

$$A \frac{dh}{dt} = q_{in} - q_{out} \qquad (2)$$

Where q = volumetric flow rates (m^3/min)

The outflow is described by:

$$q_{out} = K\sqrt{h} \qquad (3)$$

Where $K = C_V \sqrt{g}$

C_V = valve constant (m^2)

g = specific gravity (m/min^2)

And therefore the material balance equation becomes:

$$A\frac{dh}{dt} = q_{in} - K\sqrt{h} \tag{4}$$

The problem now is that $\sqrt{h}$ is a non-linear term which cannot be Laplace transformed. The good news is that if the outflow is laminar, then $q_{out} \approx Kh$ and the Equation 4 becomes:

$$A\frac{dh}{dt} = q_{in} - Kh \tag{5}$$

This is a first order equation, linear differential equation which can be Laplace transformed to give:

$$AsH(s) = Q_{in}(s) - KH(s) \tag{6}$$

Next, if the inflow as the input variable and the tank level as the output variable, equation 6 becomes:

$$H(s)\left[As + K\right] = Q_{in}(s) \tag{7}$$

$$\frac{H(s)}{Q_{in}(s)} = \frac{K_n}{\tau_1 s + 1} = G_n(s) \tag{8}$$

When $$K_n = \frac{\Delta output}{\Delta input} = {}^{1}\!/\!_{K} \tag{9}$$

$$\tau_1 = {}^{A}\!/\!_{K} \tag{10}$$

Again, now that the transfer functions can be represented as a single block as follows:

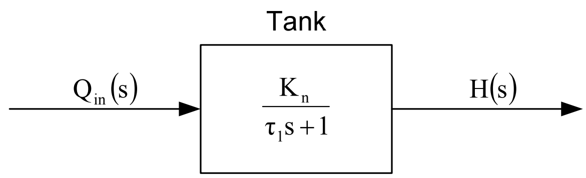


Figure 6 Block diagram of tank level process

Note that in this transfer function, K_n is the static gain and τ_1 is a time constant which how quickly the process responds to a changing input signal. These factors are used in describing the process's responses.

2.2 Energy balance

Rate of accumulation = Energy flow rate in – Energy flow rate out + Energy supplied flow rate of energy in the tank

$$\frac{d\left[\rho A h C_p\left(T_{out}-T_{ref}\right)\right]}{dt}=\rho q_{in} C_p\left(T_{in}-T_{ref}\right)-\rho q_{out} C_p\left(T_{out}-T_{ref}\right)+Q \quad (11)$$

Where
ρ = density of liquid (kg/m^3)
V = volume of a tank m^3
C_p = heat capacity of liquid (kJ/kg ·°C)
T = temperature (°C)
q = volumetric flow rate (m^3/min)
Q = heat from heater (kW)

The T_{ref} terms have been canceled because C_p was assumed to be constant and thus independent of temperature.

$$A\frac{d\left(hT_{out}\right)}{dt}=q_{in}T_{in}-q_{out}T_{out}+\frac{Q}{\rho C_p} \quad (12)$$

Equation 12 can be simplified by expanding the accumulation term using the "chain rule" for differentiation of a product

$$A\frac{d\left(hT_{out}\right)}{dt} = Ah\frac{dT_{out}}{dt} + AT_{out}\frac{dh}{dt} \tag{13}$$

Substituting Equation 13 into Equation 12, the energy balance becomes:

$$Ah\frac{dT_{out}}{dt} + AT_{out}\frac{dh}{dt} = q_{in}T_{in} - q_{out}T_{out} + \frac{Q}{\rho C_p} \tag{14}$$

But the second term of left hand side is similar Equation2. Consequently Equation 14 becomes:

$$Ah\frac{dT_{out}}{dt} + T_{out}\left(q_{in} - q_{out}\right) = q_{in}T_{in} - q_{out}T_{out} + \frac{Q}{\rho C_p} \tag{15}$$

$$\rho C_p V\frac{dT_{out}}{dt} = \dot{w}_{in} C_p\left(T_{in} - T_{out}\right) + Q \tag{16}$$

The Equation 16 can be Laplace transformed to give:

$$\rho C_p VsT(s) = \dot{w}_{in} C_p\left(T_{in}(s) - T_{out}(s)\right) + Q(s) \tag{17}$$

$$C_p T_{out}(s)\left[\rho Vs + \dot{w}_{in}\right] = \dot{w}_{in} C_p T_{in}(s) + Q(s) \tag{18}$$

$$T_{out}(s)\left[\frac{\rho Vs}{\dot{w}_{in}} + 1\right] = T_{in}(s) + \frac{Q(s)}{\dot{w}_{in} C_p} \tag{19}$$

$$T_{out}(s) = Q(s)\frac{1/\dot{w}_{in} C_p}{\rho V/\dot{w}_{in} s + 1} + T_{in}(s)\frac{1}{\rho V/\dot{w}_{in} s + 1} \qquad (20)$$

Where $$\tau = \frac{\rho V}{\dot{w}_{in}}$$

If there is a change in Q(t) only, Then $T_{in}(t) = 0$ and the transfer function relating T_{out} to Q is

$$\frac{T_{out}(s)}{Q(s)} = \frac{1/\dot{w}_{in} C_p}{\tau s + 1} \qquad (21)$$

If there is a change in $T_{in}(t)$ only, Then $Q(t) = 0$ and the transfer function relating T_{out} to T_{in} is

$$\frac{T_{out}(s)}{T_{in}(s)} = \frac{1}{\tau s + 1} \qquad (22)$$

A block diagram is equivalent below figure.

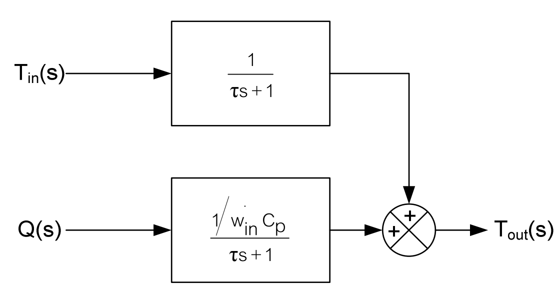


Figure 7 Block diagram of energy balance

Finally, the dynamic models of mass and energy balance are

$$\frac{dh}{dt}=\frac{q_{in}-q_{out}}{A} \tag{23}$$

$$\frac{dT_{out}}{dt}=\frac{\dot{w}_{in}\left(T_{in}-T_{out}\right)}{Ah}+\frac{Q}{Ah\rho C_p} \tag{24}$$

2.3 Degree of freedom

The degree of freedom can be calculated from the following expression

Degree of freedom = (Number of variables) – (Number of equations)

$$N_F=N_V-N_E \tag{25}$$

3 parameters: A, ρ, C_p

6 variables ($N_V = 6$): $h, q_{in}, q_{out}, T_{in}, T_{out}, Q$

2 equations ($N_E = 2$): Equations 23 and 24

These models assumed that A, ρ, C_p are parameters with given constant value depending on physical property of liquid and the geometry of tanks. Thus the degree of freedom is $N_F = 6-2 = 4$. This implies that four extra pieces of information need to be supplied to define a unique solution. This is achieved by specifying the input variables as follows:

2 disturbance variables: q_{in}, T_{in}

2 manipulated variables: q_{out}, Q

With these assigned values variables, the problem has zero degree of freedom and a unique solution is possible.

2.4 Process Transfer Function

In this work, the level step change is used to find the process transfer function.

From Equation 10, the process gain is

$$K_n = \frac{\Delta output}{\Delta input} = \frac{\Delta H}{\Delta Q_{out}} = \frac{(0.11\text{-}0.07)\,m}{(0.00528\text{-}0.00462)\,m^3/min} = 60.61\ \ min/m^2$$

From Equation 10, the process time constant is

$$K = \frac{1}{K_n} = \frac{1}{60.61\ \ min/m^2} = 0.0165\ \ m^2/min$$

$$\tau_1 = \frac{A}{K} = \frac{0.1164m^2}{0.0165\,m^2/min} = 7.055\ min$$

Finally, the transfer function is

$$G_p = \frac{60.61}{7.055s+1} \tag{26}$$

Temperature step change

From Equation 20

$$K_n = \frac{1}{\dot{w}_{in}\ C_p} = \frac{1}{0.66\,kg/min\ 0.456kJ/kg\times C°} = 3.323\,\frac{min\times C°}{kJ}$$

From Equation 20 the process time constant is

$$\tau = \frac{\rho V}{\dot{w}_{in}} = \frac{1000 \times 0.00465}{0.66} = 1.4 \text{ min}$$

Finally, the transfer function is

$$G_p = \frac{3.323}{1.4s+1} \tag{27}$$

Finally, Equations 26 and 27 will be used for IMC. It will be discuss in later.

2.5 The response of first-order systems in series

Very often a physical system can be represented by several first-order processes connected in series. To illustrate this type of system, consider the liquid level systems shown in Figure 7 in which two tanks are arranged so that the outflow from the first tank is the inlet flow to the second tank. The variation in h_2 in tank 2 affects the transient response occurring in tank 1. In contrast to this, this system is said to be interacting because the flow through R_1 now depends on the difference between h_1 and h_2.

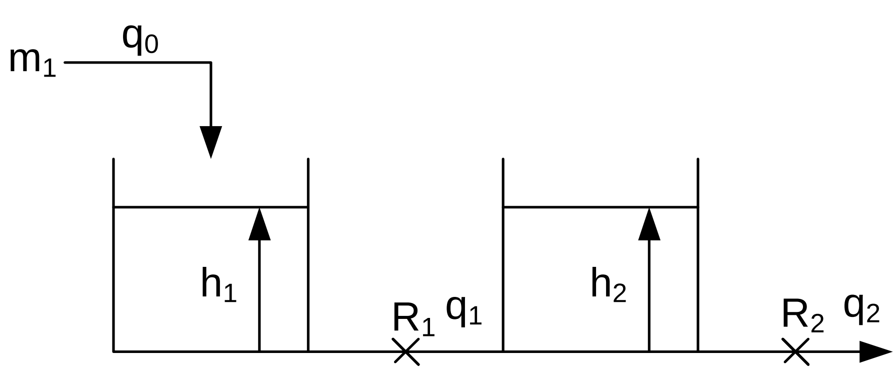


Figure 8 Two-tank interacting level system

Since each tank has control valve to control the level, the decentralized control technique is used to solve interaction effect problem.

Now, consider the same process of Figure 8 in which there are two outputs (h_1 and h_2). A change in m_1 alone will affect both outputs (h_1 and h_2). The interaction between inputs and outputs can be seen more clearly by the block diagram of Figure 9. In this diagram, the transfer functions show simultaneous effect from input to both outputs. For example, effects by only M_1, the response of H_1 and H_2 are

$$H_1(s)=G_{11}(s)M_1(s)$$
$$H_2(s)=G_{21}(s)M_1(s)$$

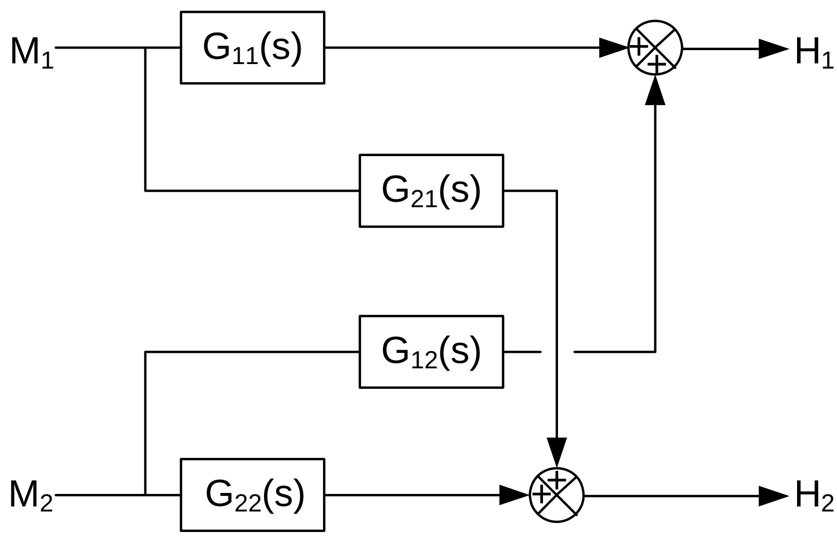


Figure 9 Block diagram of interacting process

If both H_1 and H_2 are controlled, only single control loop cannot be sufficient. In this case two control loops are needed.

2.6 Control of interacting systems

The problem of controlling the outputs of an MIMO system will be discussed by mean of a 2×2 system as shown in Figure 10. It can be extended to the case of more than two pairs of inputs and outputs by the same procedure describe here. The objective is to control C_1 and C_2 independently, in spite of changes in M_1 and M_2.

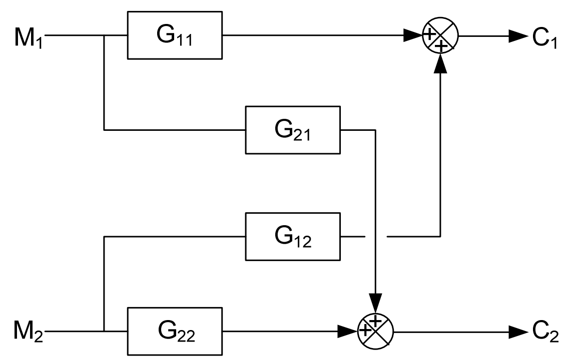


Figure 10 MIMO system for two pairs of inputs and outputs

Figure 11 shows the control loop of MIMO system for two pairs of inputs and outputs.Each loop has blocks for the controller, the valve, and measuring element. In principle, the multiloop control system of Figure 11 will maintain control if C_1 and C_2 have no effect. However, because of the interaction present in the system, a change in R_1 will also cause C_2 to vary because a disturbance enters the lower loop through the transfer function G_{21}. Because of interaction, both output (C_1 and C_2) will change if a change is made in either input alone. If G_{21} and G_{12} provide weak interaction, the two-controller scheme will give satisfactory control. If $G_{12} = G_{21} = 0$, we have no interaction and the two control loops are isolated from each other and the structure becomes multi SISO.

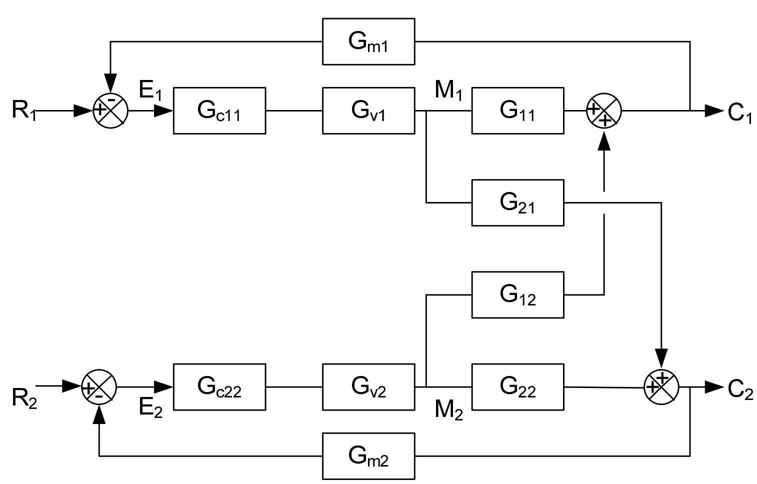


Figure 11 Multiloop control system with two controllers

To completely eliminate the interaction between outputs and set points, two more controllers (cross-controllers) are added to the system Figure 11 to give the diagram as shown in Figure 12. In principle, these cross-controllers can eliminate interaction. The following analysis, which is expressed in matrix form, will lead to the method of design for cross-controllers.

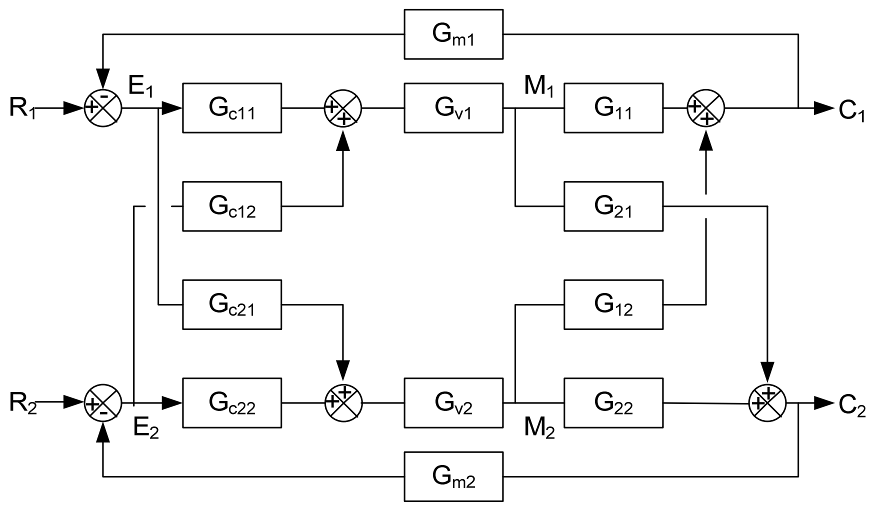


Figure 12 Multiloop control systems control with two cross-controllers

2.7 Error checking

The criteria of this category are based on the entire response of the process. This work used IAE shown in Equation 28.

$$IAE=\int_{0}^{\infty} \left|e(t)\right| dt \tag{28}$$

This process is suppression of small error that is suitable for IAE.

After the model is observed for these systems, the next part, controllers design is illustrated to control system. The each of controller has different algorithm and advantage, which depend on characteristic of processes. Next topic, the controllers designed are considered.

3. To design the variety controllers by using LabVIEW 8.0.

Since each controller has a different algorithm to derive, this topic will show the design of controllers. This work has various designed controllers, PID, IMC, GMC, and FLC.

3.1 Proportional Integral Derivative

Currently, the Proportional-Integral-Derivative (PID) algorithm is the most common control algorithm used in industry. In this work, PID was used to control processes that include level and heat control. A PID controller determines a controller output value, such as the valve position or heater power. The controller applies the controller output value to the system, which in turn drives the process variable toward the set point value.

The PID controller compares the set point (SP) to the process variable (PV) to obtain the error (e).

$$e = SP - PV \tag{29}$$

Then the PID controller calculates the controller action, u(t), where Kc is controller gain.

$$u(t) = K_c \left(e + \frac{1}{T_i} \int_0^t e\,dt + T_d \frac{de}{dt} \right) \tag{30}$$

If the error and the controller output have the same range, –100% to 100%, controller gain is the reciprocal of proportional band. Ti is the integral time in minutes, also called the reset time, and Td is the derivative time in minutes, also called the rate time. The following formula represents the proportional action.

$$u_P(t) = K_c \times e(t) \tag{31}$$

The following formula represents the integral action.

$$u_I(t) = \frac{K_c}{T_t} \int_0^t edt \tag{32}$$

The following formula represents the derivative action.

$$u_D(t) = K_c T_d \frac{de}{dt} \tag{33}$$

Implementing the PID algorithm with the PID VIs

This section describes how the PID VIs implement the positional PID algorithm. The subVIs used in these VIs is labeled so you can modify any of these features as necessary.

The following formula represents the current error used in calculating proportional, integral, and derivative action.

$$e(k) = (SP - PV_f) \tag{34}$$

Proportional Action is the controller gain times the error, as shown in the following formula.

$$u_P(k) = (K_c \times e(k)) \tag{35}$$

Trapezoidal Integration is used to avoid sharp changes in integral action when there is a sudden change in PV or SP. Use nonlinear adjustment of integral action to counteract overshoot.

$$u_I(k) = \frac{K_c}{T_i}\sum_{i=1}^{k}\left[\frac{e(i)+e(i-1)}{2}\right]\Delta t \tag{36}$$

Because of abrupt changes in SP, only apply derivative action to the PV, not to the error e, to avoid derivative kick. The following formula represents the Partial Derivative Action.

$$u_D(k) = -K_c\frac{T_d}{\Delta t}\left(PV_f(k) - PV_f(k-1)\right) \tag{37}$$

Controller output is the summation of the proportional, integral, and derivative action, as shown in the following formula.

$$u_k(k) = u_P(k) + u_I(k) + u_D(k) \tag{38}$$

The actual controller output is limited to the range specified for control output.

If $u(k) \geq u_{max}$ then $u(k) = u_{max}$

and

if $u(k) \leq u_{min}$ then $u(k) = u_{min}$

The following formula shows the practical model of the PID controller.

$$u(t) = K_c\left[(SP - PV) + \frac{1}{T_i}\int_0^t (SP - PV)dt + T_d\frac{dPV_f}{dt}\right] \tag{39}$$

Equation 39 gives the velocity form of the digital PID algorithm:

$$\Delta u_k = u_k - u_{k-1} = K_c \left[\left(e_k - e_{k-1} \right) + \frac{\Delta t}{T_i} e_k + \frac{\tau_d}{\Delta t} \left(e_k - 2e_{k-1} + e_{k-2} \right) \right] \qquad (40)$$

The velocity form has three advantages

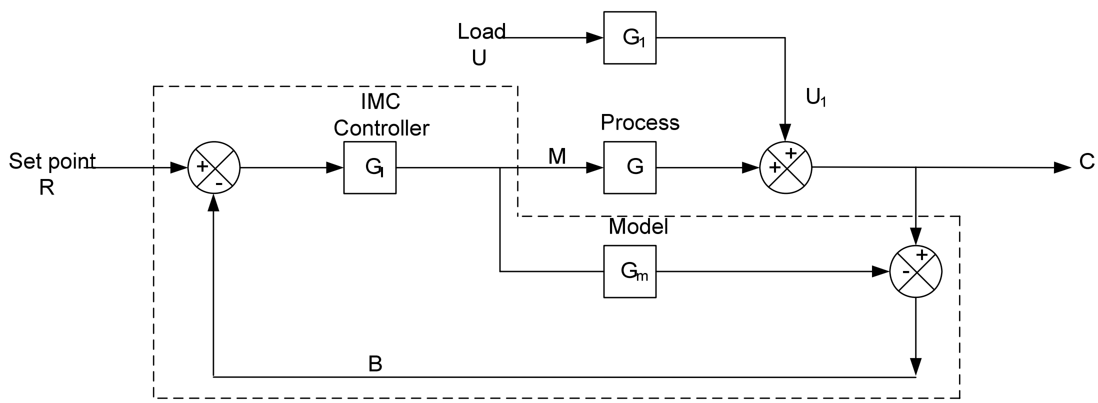
1. Inherently contains anti-reset windup because the summation of error is not explicitly calculated.

2. This output is expressed in a form that can be utilized directly by some final control element.

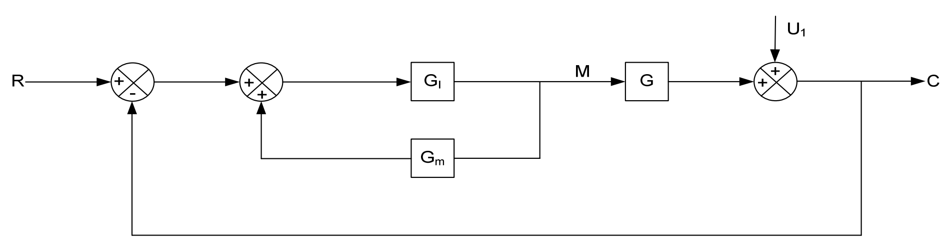
3. This form does not require any initialization of the output.

3.2 Internal Model Control

A block diagram of an IMC system is shown in Figure 13. G is the transfer function of the process and G_m is the model of the process. Although G and G_m are called the transfer function of the process, they actually include the valve and the process. The transfer function of the measuring element is taken as 1.0. The portion of the diagram implemented by computer includes the IMC controller and the model; this portion is surrounded by the dotted boundary.



(a)



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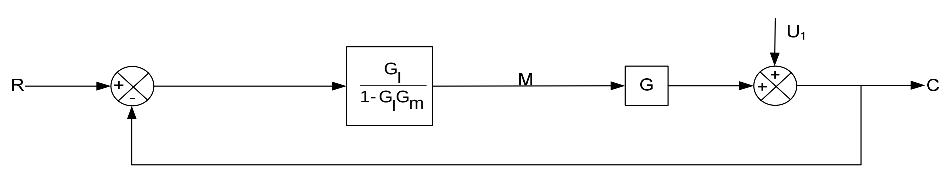

(c)

<u>Figure 13</u> Internal Model Control structures: (a) basic structure, (b) alternate structure, (c) structure equivalent to conventional control

In order to compare the IMC structure of Figure 13a with the conventional control structure, its diagram of Figure 13a has been rearranged as shown in Figure 13b. For the convenience, the transfer function through which the load U passes has been omitted. The structure in Figure 13b can use to relate the IMC controller to the conventional controller. Replacing the inner loop of Figure 13b with a single block gives the structure shown in Figure 13c. Since this structure is the conventional single loop control structure, we can identify the single controller block as G_c. After one designs the IMC controller (G_I) by the method to be described, one can determine the equivalent conventional controller G_c by the relation

$$G_c = \frac{G_I}{1 - G_I G_m} \tag{41}$$

For the structure shown in Figure 13a, the equation is

$$C = U_1 + \frac{G G_I}{1 + G_I (G - G_m)} \left[R - U_1 \right] \tag{42}$$

If the model exactly matches the process (i.e., $G_m = G$), the only signal entering comparator 1 in Figure 13a is U_1. Since U_1 is not the result of any processing by the transfer functions in the forward loop, U_1 is not a feedback signal but an independent signal that is equivalent to R in its effect the C. In fact, there is no feedback when $G = G_m$ and we have an open-loop system as shown in Figure 14. In this case the stability of the control system depends only on G_I and G_m which are stable; the control system is stable too.

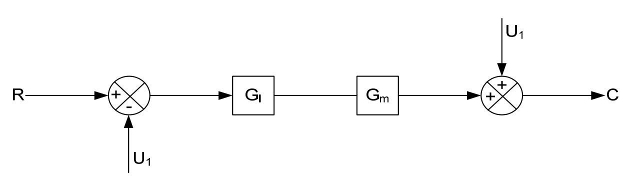

Figure 14 Structure when model match process ($G_m = G$)

Ideally, C tracks R without lag when only a set point change occurs. In order to occur, Figure 14 or Equation 42 is shown that $G_I G_m = 1$. Solving for G_I gives

$$G_I = \frac{1}{G_m} \tag{43}$$

Equation 43 simply states that the IMC controller should be the inverse of the transfer function of the process model. Keep in mind that Equation 43 is based on the assumption that the model exactly matches the process.

For the case only a change in load U_1, the output C remains unchanged. In order to occur, we see again from Figure 14 or Equation 42 will usually lead to a transfer function that cannot be implemented because it will be unstable, requires pure differentiation. For example, if $G_m = \frac{1}{(\tau s+1)}$, the application of Equation 43 gives

$$G_I = \tau s + 1$$

This result is equivalent to an ideal PD controller, which cannot be implemented because of the derivative term. If $G_m = \frac{e^{-\tau s}}{\tau s+1}$, G_I becomes

$$G_I = (\tau s+1)e^{-\tau s}$$

The term $e^{\tau s}$, which represents prediction, cannot be implemented.

IMC Controller Design

In using these rules, only a step change in disturbance is considered. The procedure for disturbances other than a step response is more complicated and beyond the scope of the limited discussion presented here.

1. Separate the process model G_m into two terms

$$G_m = G_{m_a} G_{m_m} \tag{44}$$

Where G_{m_a} is a transfer function of an all-pass filter. An all-pass filter is one for which $\left|G_{m_a}(j\omega)\right| = 1$ for allω. Examples are $e^{-\tau_d s}$ and (1-s)/(1+s). G_{m_m} is a transfer function that has minimum phase characteristics. A system has non-minimum phase characteristics if its transfer function contains zeros in the right half plane or transport lags, or both. Otherwise, a system has minimum phase characteristic. For a step change in disturbance G_I is determined by

$$G_I = 1/G_{m_m} \tag{45}$$

The results of Equation 45 will yield a transfer function that is stable and does not require prediction; however, it will have terms that cannot be implemented because they require pure differentiation.

2. To obtain a practical IMC controller, one multiplies G_I in step 1 by a transfer function of a filter, f(s). The simplest form recommended by Morari and Zafiriou is given by

$$f(s) = \frac{1}{(\lambda s + 1)^n} \tag{46}$$

Where λ a filter parameter and n is an integer. The practical IMC controller can be expressed as

$$G(I) = \frac{f}{G_{m_m}} \tag{47}$$

The value of n is selected large enough to give a result for G_I that does not require pure differentiation. The usual choice is n = 1. For the simple treatment of IMC design presented here, λ will be considered as a tunable parameter.

3. If one wants to obtain the conventional controller transfer function G_c, use is made of Equation 41, with G_I obtained from Equation 45. For many simple process models, G_c turns out to be equivalent to a PID controller multiplied by a first-order transfer function; thus

$$G_c = K_c\left(1+\tau_D s+\frac{1}{\tau_I s}\right)\left(\frac{1}{\tau_1 s+1}\right) \tag{48}$$

Where K_c, τ_D, τ_I and τ_1 are functions of λ and the parameter in G_I and G_m.

Internal Model Control for this plant

When one tank process is first order

$$G_m = \frac{K}{\tau s+1} \tag{49}$$

$$G_I = \frac{1}{G_{m_m}}\times f = \frac{1}{K}\times\frac{\tau s+1}{\lambda s+1} \tag{50}$$

$$G_c = \frac{\tau}{\lambda K}\left(1+\frac{1}{\tau s}\right) \tag{51}$$

This result is in the form of a PI controller:

$$G_c = K_c\left(1+\frac{1}{\tau_I s}\right) \qquad K_c = \frac{\tau}{\lambda K} \qquad \tau_I = \tau$$

The IMC controller is realized through a software program and the appropriate discrete-time input is same the PI controller, the only one parameter (λ) must be used to tune the controller.

3.3 Generic Model Control

This section presents the design of a controller to control a tank following a desired level and temperature trajectory. It is accepted that the use of linear control techniques in highly nonlinear and time variant chemical processes is quite limited to their performances and may give a poor control response. Therefore, in this work, a nonlinear control technique based on generic model control (GMC) algorithm is utilized. This model-based control methodology has been received much interest during the last decade [Lee and Sulivan 1988]. However, in the past, simulation has been made to apply the GMC to implement process response. Therefore, in this work, GMC is developed for the real case to control level and temperature.

GMC algorithm

Consider a process based on the following model equations:

$$\frac{dx}{dt} = f(x,p,t) + g(x,t)u \qquad (52)$$

$$y = h(x) \qquad (53)$$

Where x is a vector of state variables, y is a vector of output variables, u is a vector of input variable, p is a vector of process parameters, and f, g, and h are generally nonlinear function vectors. The general form of GMC algorithm can be written as

$$\frac{dy}{dt} = K_1(y_{sp} - y) + K_2\int_0^{t_f}(y_{sp} - y)dt \qquad (54)$$

The GMC control respond can be designed via the tuning parameters K_1 and K_2 based on the tuning curve given by [Lee and Sulivan 1988]. It should be noted that the GMC approach is a special case of global unit output linearizing control technique in which a transformed control action is chosen properly with the external PI controller. The use of Equation 54 forces y toward its set point, y_{sp}, with zero offset. If Equation 53 is substituted into the resulting equation, the GMC control law is

$$u = \frac{\left[K_1 \left(y_{sp} - y \right) + K_2 \int_0^{t_f} \left(y_{sp} - y \right) dt - \left(dh/dx \right) f\left(x, d, t \right) \right]}{\left(dh/dx \right) g\left(x, t \right)} \tag{55}$$

GMC controller Design

In this work, GMC can be divided into 3 cases because each case based on the manipulated variable of model. The first case is a tank level control; the second case is a tank temperature control, and the third case is a two interacting tank control. To implement the GMC, a mass and energy balance around the tank is required. It gives a relation between the controlled variable and the manipulated variable.

The first case tank level control

$$\frac{dh}{dt} = \frac{q_{in} - q_{out}}{A} \tag{56}$$

Manipulated variable is q_{out}

$$q_{out} = q_{in} - A \frac{dh}{dt} \tag{57}$$

Rearranging the Equation 57 as in form of GMC algorithm (Equation 55), the following functions, f, g, and h can be defined

$$f(x,p,t) = \frac{q_{in}}{A} \tag{58}$$

$$g(x,t) = -\frac{1}{A} \tag{59}$$

$$h(x) = h \tag{60}$$

Replacing these equations in Equation 55, we have

$$q_{out} = q_{in} - A\left(K_1\left(h_{sp} - h\right) + K_2\int_0^t\left(h_{sp} - h\right)dt\right) \tag{61}$$

In order to make GMC control law available for an implementation, the integral term in Equation 61 is approximated by numerical integration. This leads to discrete time form of the GMC algorithm as given in the following equation.

$$q_{out}(k) = q_{in}(k) - A\left(K_1\left(h_{sp} - h(k)\right) + K_2\sum_0^k\left(h_{sp} - h(k)\right)\Delta t\right) \tag{62}$$

Where Δt is the sampling time.

The second case tank temperature control

For the this case, based on the assumption that the amount of the heat accumulated in the walls of tank is negligible compares to the heat transferred in the tank, the energy balance equation becomes

$$\frac{dT_{out}}{dt} = \frac{q_{in}\left(T_{in} - T_{out}\right)}{Ah} + \frac{Q}{Ah\rho C_p} \tag{24}$$

Rearranging the Equation 24 as in the form of GMC algorithm, the following functions, f, g, and h can be defined.

$$f(x,p,t)=\frac{q_{in}T_{in}-q_{in}T_{out}}{Ah} \tag{63}$$

$$g(x,t)=\frac{1}{Ah\rho C_p} \tag{64}$$

$$h(x)=T_{out} \tag{65}$$

Replacing these equations in Equation 55, we have

$$Q=\rho AhC_p\left(K_1\left(T_{outsp}-T_{out}\right)+K_2\int_0^{t_f}\left(T_{outsp}-T_{out}\right)dt\right)-q_{in}\rho C_p\left(T_{in}-T_{out}\right) \tag{66}$$

Discrete-time form of Equation 65 can be in the following equation.

$$Q=\rho AhC_p\left(K_1\left(T_{outsp}-T_{out}(k)\right)+K_2\sum_0^k\left(T_{outsp}-T_{out}(k)\right)\Delta t\right)-q_{in}\rho C_p\left(T_{in}(k)-T_{out}(k)\right) \tag{67}$$

The third case two-interacting tank control

$$\frac{dh_1}{dt}=\frac{q_0-q_1}{A_1}$$

$$\frac{dh_2}{dt}=\frac{q_1-q_2}{A_2} \tag{68}$$

Therefore, the continuous form of equation 68 is

$$q_1 = q_0 - A_1\left[K_1\left(h_{1sp} - h_1\right) + K_2\int_0^{t_f}\left(h_{1sp} - h_1\right)dt\right]$$

$$q_2 = q_1 - A_2\left[K_3\left(h_{2sp} - h_2\right) + K_4\int_0^{t_f}\left(h_{2sp} - h_2\right)dt\right] \qquad (69)$$

And the discrete form of equation 69 is

$$q_1 = q_0(k) - A_1\left[K_1\left(h_{1sp} - h_1(k)\right) + K_2\sum_0^{k}\left(h_{1sp} - h_1(k)\right)\Delta t\right]$$

$$q_2 = q_1(k) - A_2\left[K_3\left(h_{2sp} - h_2(k)\right) + K_4\sum_0^{k}\left(h_{2sp} - h_2(k)\right)\Delta t\right] \qquad (70)$$

Finally, Equation 70 is used to develop GMC controller in order to control system.

3.4 Fuzzy Logic Control

Engineers normally consider physical variables in a qualitative. However, qualitative information can also be very useful both in engineering and everyday life. For example, a person in a shower is aware of whether the water temperature is too warm, too cold and or just right. An accurate temperature measurement is not necessary. Also, such qualitative information can be used to good advantage for feedback control. For example, if the shower temperature is too cold and the flow rate is too low, the person would increase the hot water flow rate. In the process industries, experienced plant operators sometimes take control actions based on qualitative information, such as the observed color of uniformity of a solid material.

Fuzzy logic is a method of rule-based for making a decision and used for expert systems and process control that emulates the rule-of-thumb thought process that human beings use. Lotfi Zadeh developed fuzzy set theory, the basis of fuzzy logic, in the 1960s. Fuzzy set theory differs from traditional Boolean set theory in that fuzzy set theory allows for partial membership in a set. Traditional Boolean set theory is two-valued in the sense that a member either belongs to a set or does not, which is represented by a one or zero, respectively. Fuzzy set theory allows for partial membership, or a degree of membership, which might be any value along the continuum of zero to one. A type of fuzzy set called a *membership function* can be used to quantitatively define a linguistic term. A membership function specifically defines degrees of membership based on a property such as temperature or pressure. With membership functions defined for controller or expert system inputs and outputs, a rule base of IF-THEN type conditional rules can be formulated. Then, with fuzzy logic inference, the rule base and corresponding membership functions can be used to analyze controller inputs and determine controller outputs. After a fuzzy controller is defined, we can quickly and easily implement process control. Most traditional control algorithms require a mathematical model to work on, but many physical systems are difficult or impossible to model mathematically. In addition, many processes are either nonlinear or too complex for you to control with traditional strategies. FLC has been used in consumer products such as washing machine, vacuum cleaner. It has also been applied to industrial control problem.

Structure of a Fuzzy controller

A fuzzy controller is composed of the following three calculation steps: fuzzification, fuzzy inference, and defuzzification. Linguistic rules integrated into the rule base of the controller implement the control strategy that it is based on engineering experience with respect to a closed-loop control application. A fuzzy controller has a static and deterministic structure, as shown in Figure 15.

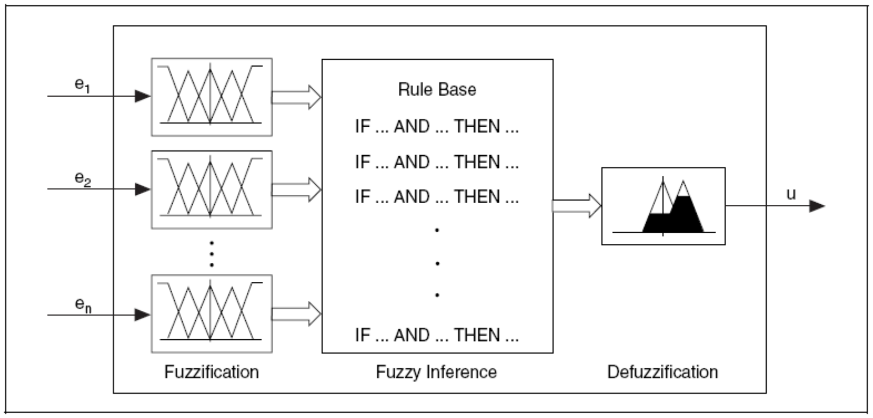

Figure 15 Internal structure of a Fuzzy controller
Source: National Instruments (2003)

There are many different ways to use fuzzy controllers in closed-loop control applications. The most basic structure uses the sensor signals from the process as input signals for the fuzzy controller and the outputs as command values to drive the actuators of process. A corresponding control loop structure is shown in Figure 16.

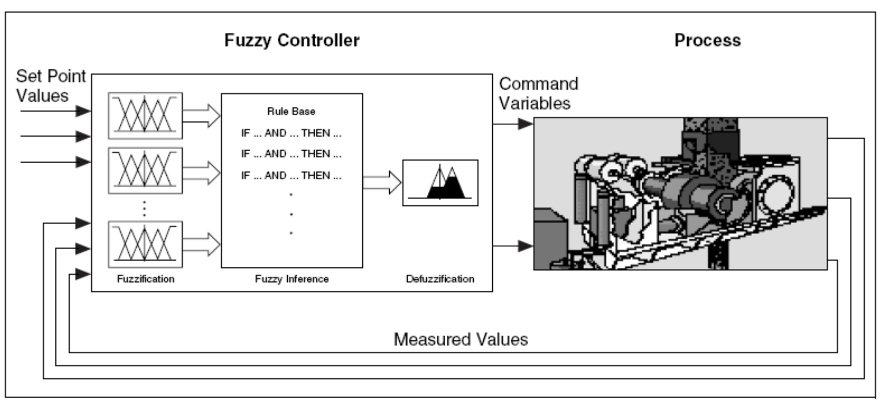

Figure 16 Simple Closed-Loop Control Structure with Fuzzy Controller
Source: National Instruments (2003)

Within the system design step, all of the linguistic variables and terms for the given application must be established as the vocabulary of the rule-based system. Use the rule base to formulate the control strategy, and then select an appropriate defuzzification method.