PROCESS CONTROL AND INSTRUMENTATION IN MINERAL PROCESSING OPERATION

LECTURE NOTES

Compiled by

SUSHANTA KUMAR PRADHAN
Assistant Professor
Department of Mineral Engineering
Government College of Engineering, Keonjhar, Odisha

DISCLAIMER

THIS DOCUMENT DOES NOT CLAIM ANY ORIGINALITY AND CANNOT BE USED AS A SUBSTITUTE FOR PRESCRIBED TEXTBOOKS. THE INFORMATION PRESENTED HERE IS MERELY A COLLECTION FROM DIFFERENT REFERENCE BOOKS AND INTERNET CONTENTS. THE OWNERSHIP OF THE INFORMATION LIES WITH THE RESPECTIVE AUTHORS OR INSTITUTIONS.

PROCESS CONTROL & INSTRUMENTATION (3-1-0)

MODULE-I **(10 hours)**

Introduction: Need for process control; justification in terms of overall technical and economic benefits. Fundamental Aspects: Recognition of dynamic nature of control operation; identification of controllable and non-controllable operating variables; need for obtaining quantitative relationships for describing the effect of controllable operating variables on process performance; defining control objectives; identification of process and plant constraints

MODULE-II **(10 hours)**

Basic Data Required for Control System Design: Ways of obtaining data for control system design; Nature and frequency of process disturbances; investigating basic properties of process response (impulse and step response).

MODULE-III **(10 hours)**

Types of Control Actions: Feed Forward and feedback control; construction of a feedback controller; proportional action, integral action and derivative action; tuning of feedback controllers; multiple input control; ratio control and cascade control.

Control of Individual Unit Operations: Crushing, grinding and flotation circuits; control of thickener and other allied operations.

MODULE-IV **(10 hours)**

Instrumentation for measurement: On-line particle size distribution, Metallurgical Grade analysis and coal analysis ; pulp density, pulp level, froth level, slurry flow rate, ball Mill load and other required measurements.

Some Published Case Studies: Some examples taken from published papers on actual implementation of control systems in an operating plant and the control strategies used.

REFERENCES:

1. Advanced Control and Supervision of Mineral Processing Plants, Edited by Daniel Sbárbaro and René del Villar, Springer

2. George Stephanopoulos: Chemical Process Control: An Introduction to Theory and Practice, PHI Learning

MODULE-I

Introduction:

Process:

The conversion of feed materials to products using chemical and physical operations.

Objectives of process:

- The objective of a process is to convert certain raw materials (input feedstock) into desired products (output) using available sources of energy in the most economical way.
- Unit process may involve either a change of chemical state or a change in physical state.
- Many external and internal conditions affect the performance of a process. These conditions may be expressed in terms of process variables such as temperature, pressure, flow, liquid level, dimension, weight, volume etc.

Requirements of Process:

A process must satisfy several requirements imposed by its designers and the general technical, economic and social conditions in the presence of ever-changing external influences (disturbances).

The requirements are

- Safety of men and machine
- Environmental regulations
- Production specifications
- Operational constructions and economics

Examples of Process:

A process may be

- Unit process like a reactor
- Unit operation like thickener, flotation column or storage vessel.

Process Control:

Process controls is a mixture between the statistics and engineering discipline that deals with the mechanism, architectures, and algorithms for controlling a process.

Or

Process control system is the arrangement of physical components and devices connected to regulate the quantity of interest at some desired value regardless of external Influences.

Some examples of controlled processes are:

- Controlling the temperature of a water stream by controlling the amount of steam added to the shell of a heat exchanger.
- Controlling the temperature of a muffle furnace or oven in laboratory
- Maintaining a set ratio of reactants to be added to a flotation column by controlling their flow rates.
- Controlling the height of fluid in a tank to ensure that it does not overflow.
- Controlling the speed of a motor

Need for process control:

The role of a process engineer is to ensure continuous operation with safety by monitoring every single process of an industry. In years past the monitoring of these processes was done at the unit and was maintained locally by operators and engineers. Today many process plants have gone to full automation, which means that engineers and operators are helped by DCS that communicates with the instruments in the field.

A control system is required to perform either one or both task:

- Maintain the process at the operational conditions and set points
- Transition the process from one operational condition to another

The need of process control can be:

- For the safety of equipment and manpower
- To ensure environmental regulations related to emission of toxic gases, waste water etc.
- To get desired product specifications
- For maintaining required operating conditions
- To ensure the reliability of the system
- To use the mathematical models effectively
- To reduce the manpower requirement for monitoring

Technical and economic benefits:

Economic Advantages:

- Improve production rate:
  A continuous and steady system can always increase production rate.
- Reduce unit cost:
  As process control reduces operating cost hence the unit cost of the final product is also less.
- Meet the customer requirement:
  In many processes the product can be produced with desired specification through efficient process control.
- Reduce the manpower cost:
  As the monitoring is being done by instruments in the field and auto operation is being done by control system, the process requires less manpower.
- Quality and reliability of the product:
  The product produced are more reliable and as per the specified quality by minimizing the disturbances.
- Easier decision making for the management:
  As the system is more reliable and efficient the management can predict the production schedule and take a decision on supply and demand.
- Reduce power consumption:
  By effective operation and control of the equipment, power requirement of the plant can be optimized.

Technical Advantages:

- Steady operation:
  The main advantage of having an automatic control system is its steadiness. In general, all processes are transient in nature, but we can achieve near steady operation by minimizing disturbances in the system.
- Reduce breakdown time:
  Efficient control of processes reduces the breakdown time.
- Improve safety of the equipment:
  In automatic control, all the parameters of equipment are kept within their allowable limit which ensures the safety of the equipment.
- Better use of raw material:
  Different raw materials have different characteristics which are called disturbances. In a manual control we may not be able to detect all these characteristics which may lead to inefficient operation. In automatic control all these disturbances can be detected and control action will be taken as required.

- Improve process efficiency by using mathematical modelling:
  Now a day's most of the processes are operated with mathematical modelling to improve process efficiency. Automatic control helps better implementation of process models.

Dynamic nature of control operation:

The term process dynamics refers to unsteady-state (or transient) process behaviour, whose behaviour changes over time.

Mathematically, the process dynamics can be described by differential equations. Unsteady-state (or transient) process behaviour then corresponds to a situation, where (at least some) time derivatives of the differential equations are nonzero. Transient operation occurs during important situations such as start-ups and shutdowns, unusual process disturbances, and planned transitions from one product grade to another. Even at normal operation, a process does not operate at a steady state, because there are always variations in external variables, such as feed composition or cooling medium temperature.

Dynamic models play a central role in the subject of process dynamics and control. The models can be used to

- Improve understanding of the process
- Train plant operating personnel.
- Develop a control strategy for a new process.
- Optimize process operating conditions.

Models can be classified based on how they are obtained:

- Theoretical models are developed using the principles of chemistry, physics, and biology.
- Empirical models are obtained by fitting experimental data.
- Semi-empirical models are a combination of the models in categories (a) and (b); the numerical values of one or more of the parameters in a theoretical model are calculated from experimental data.

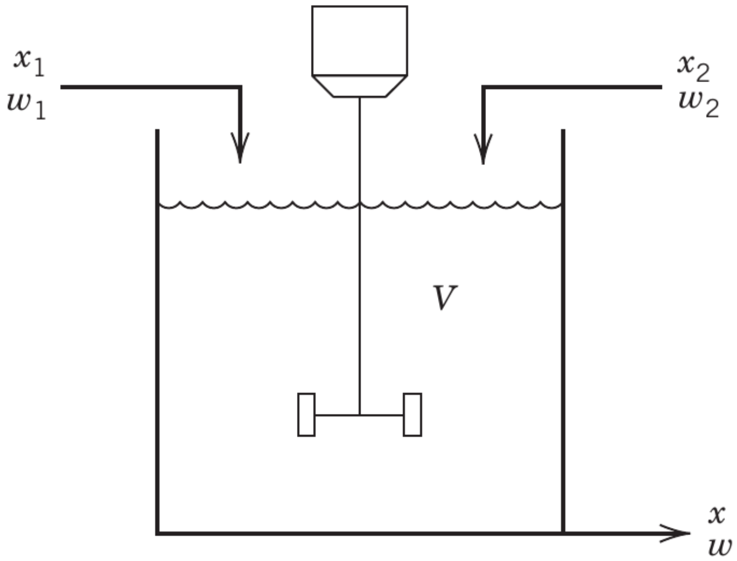
Example of a blending process:

Let us consider the isothermal stirred-tank blending system. Here the volume of liquid in the tank V can vary with time, and the exit flow rate is not necessarily equal to the sum of the inlet flow rates.

An unsteady-state mass balance for this blending system has the form

(Rate of accumulation of mass in the tank) = (Rate of mass in) – (Rate of mass out)

The mass of liquid in the tank can be expressed as the product of the liquid volume V and the density ρ.



(A liquid tank)

Consequently, the rate of mass accumulation is simply d(Vρ)/dt can be written as

$$\frac{d(V\rho)}{dt} = w_1 + w_2 - w$$

where w_1, w_2 , and w are mass flow rates.

The unsteady-state material balance for the component A can be derived in an analogous manner. We assume that the blending tank is perfectly mixed. This assumption has two important implications:

- there are no concentration gradients in the tank contents
- the composition of the exit stream is equal to the tank composition.

The perfect mixing assumption is valid for low-viscosity liquids that receive an adequate degree of agitation. In contrast, the assumption is less likely to be valid for high-viscosity liquids such as polymers or molten metals.

For the perfect mixing assumption, the rate of accumulation of component A is d(Vρx)/dt, where *x* is the mass fraction of A.

The unsteady-state component balance is

$$\frac{d(V\rho x)}{dt} = w_1x_1 + w_2x_2 - wx$$

These equations provide an unsteady-state model for the blending system.

For steady state, model can be derived by setting accumulation terms equal to zero.

$$0 = w_1 + w_2 - w$$

$$0 = w_1x_1 + w_2\,x_2 - w\,x$$

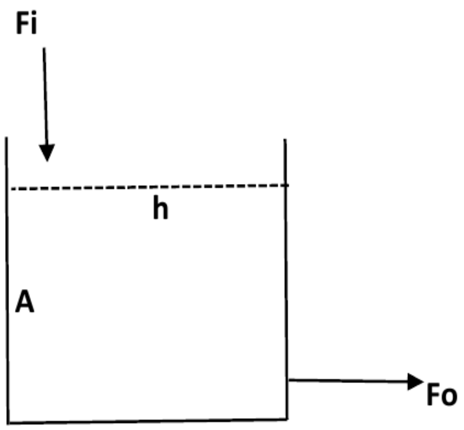
where the nominal steady-state conditions are denoted by x and w and so on.

A Systematic Approach for Developing Dynamic Models:

- State the modelling objectives and the end use of the model. Then determine the required levels of model detail and model accuracy.
- Draw a schematic diagram of the process and label all process variables.
- List all of the assumptions involved in developing the model. Try to be parsimonious: the model should be no more complicated than necessary to meet the modelling objectives.
- Determine whether spatial variations of process variables are important. If so, a partial differential equation model will be required.
- Write appropriate conservation equations (mass, component, energy, and so forth).
- Introduce equilibrium relations and other algebraic equations (from thermodynamics, transport phenomena, chemical kinetics, equipment geometry, etc.).
- Perform a degrees of freedom analysis to ensure that the model equations can be solved.
- Simplify the model. It is often possible to arrange the equations so that the output variables appear on the left side and the input variables appear on the right side. This model form is convenient for computer simulation and subsequent analysis.
- Classify inputs as disturbance variables or as manipulated variables.

Example of liquid tank system:

Let us consider a liquid tank of cross-sectional area A. The liquid input rate is Fi and the liquid output rate is Fo. The height of the liquid is denoted by h.



(Liquid tank)

Modelling equation of the system can be derived as

Rate of accumulation = Rate of input – Rate of output

Or $$A\frac{dh}{dt} = Fi - Fo$$

Case-I:

If Fo is directly proportional to h or $Fo = \beta h$

So the above equation can now be written as:

$$A\frac{dh}{dt} = Fi - \beta h$$

$$\text{Or} \quad A\frac{dh}{dt} + \beta h = Fi$$

Now this is a linear differential equation.

Case-II:

If Fo is directly proportional to $\sqrt{h}$ or $Fo = \alpha\sqrt{h}$

So the above equation can now be written as:

$$A\frac{dh}{dt} + \alpha\sqrt{h} = Fi$$

Now the term $\alpha\sqrt{h}$ is in non-linear form hence the equation is a non-linear differential equation. We need to first linearize the equation to get the solution.

Transfer Function (G(s)):

The transfer function is defined as the ratio of the output and the input in the Laplace domain.

Modelling equations are represented in 't' domain, but transfer functions are represented in 's' domain or Laplace domain.

Consider a SISO system,

(Transfer Function)

The transfer function of this system is given as

Transfer function = $\frac{\text{Output}(S)}{\text{Input}(S)}$

Or G(s) = $\frac{Y(s)}{F(s)}$

Where Y(s) and F(s) are the Laplace transform of y(t) and f(t) respectively.

Laplace function represent the linear or linearized input/ output model in terms of deviation variables.

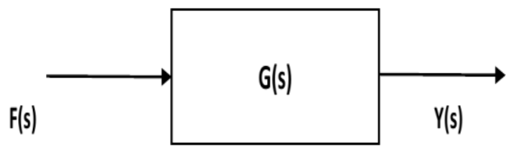
General rules to develop a transfer function

- Make unsteady state balance (mass, heat or momentum)
- Make steady state balance
- Subtract the steady state equation from the unsteady state equation.
- Transform the resulting equation into the Laplace domain
- Rearrange the equation to get the ratio of the (out/in) in one side and the other parameters in the other side (the resulting is the transfer function).

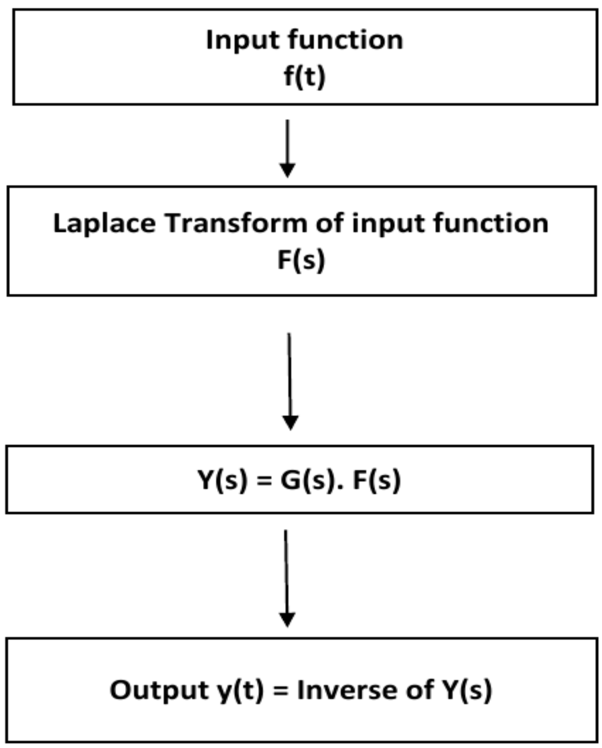
Development of Block Diagram:

A block diagram is a pictorial representation of the cause and effect relationship between the input and output of a physical system. A block diagram provides a means to easily identify the functional relationships among the various components of a control system.

The simplest form of a block diagram is the block and arrows diagram. It consists of a single block with one input and one output. The block normally contains the name of the element or the symbol of a mathematical operation to be performed on the input to obtain the desired output. Arrows identify the direction of information or signal flow.

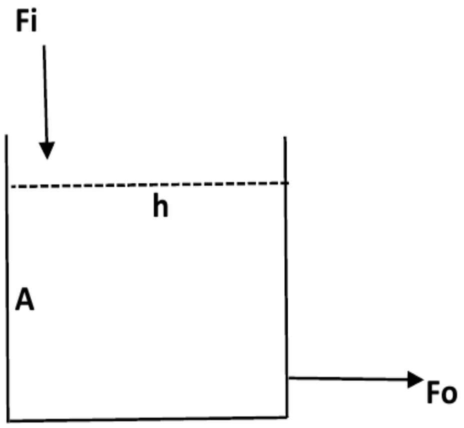


The process of input to output change can be illustrated as follows:



Derivation of transfer function: (Example of liquid tank system):

Let us consider the liquid tank system which is earlier discussed. The derivation of transfer function includes four steps.



Step-I: (Development of the model)

The model can be described as

$$A\frac{dh}{dt} = Fi - Fo$$

Step-II:(Construction of the model in terms of deviation variables)

At steady state the model can be written as:

$$A\frac{dh_s}{dt} = Fis - Fos$$

Where ‘s’ represents steady state

Model can be developed by subtracting the generalized model to the steady state model and can be written as:

$$A\frac{dh'}{dt} = Fi' - Fo'$$

Where $h' = h - h_s$

$Fi' = Fi - Fis$

$Fo' = Fo - Fos$

Step-III: (Taking Laplace transformation of the new model)

Taking Laplace transform of the above equation we get:

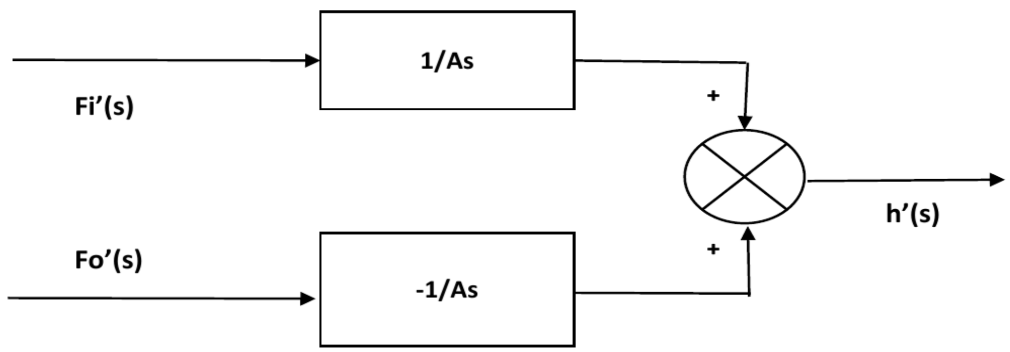
$$A.s.h'(s) = Fi'(s) - Fo'(s)$$

Where h'(s), Fi'(s) and Fo'(s) are Laplace transform

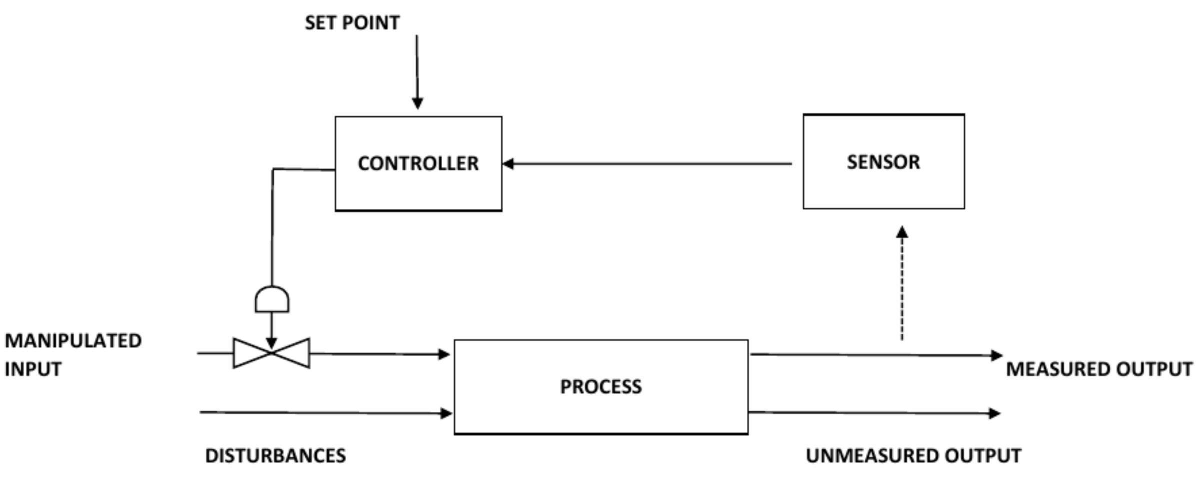
Or h'(s) = (1/As).Fi'(s) – (1/As).Fo'(s)

Here 1/As is the transform function.

Step-IV: (Make Block Diagram)



Identification of controllable and non-controllable operating variables:



(Conceptual Block diagram of a control system)

In controlling a process there exist two types of classes of variables.

a. **Input Variable:**

This variable shows the effect of the surroundings on the process. It normally refers to those factors that influence the process. An example of this would be the flow rate of the steam through a heat exchanger that would change the amount of energy put into the process. There are effects of the surrounding that are controllable and some that are not. These are broken down into two types of inputs.

- Manipulated inputs: The process variables that can be adjusted in order to keep the controlled variables at or near their set points.
- Disturbances: inputs that cannot be controlled by an operator or control system and cause the controlled variables to deviate from their respective set points. There exist both measurable and immeasurable disturbances.

b. **Output variable/ Control variable:**

These are the variables that can be controlled. An example of this would be the amount of any gas that comes out of a reaction. These variables may or may not be measured. The desired value of a controlled variable is referred to as its set point.

As we consider a controls problem, we are able to look at two major control structures.

- Single input-Single Output (SISO)-

for one control(output) variable there exist one manipulate (input) variable that is used to affect the process.

- Multiple input-multiple output(MIMO)-

There are several control (output) variable that are affected by several manipulated (input) variables used in a given process.

Guidelines for selection of variables:

Controlled Variables:

- All variables that are not self-regulating must be controlled.
- Choose output variables that must be kept within equipment and operating constraints (e.g., temperatures, pressures, and compositions)
- Select output variables that are a direct measure of product quality (e.g., composition, refractive index) or that strongly affect it (e.g., temperature or pressure).
- Choose output variables that seriously interact with other controlled variables.
- Choose output variables that have favourable dynamic and static characteristics.

Manipulated Variables:

- Select inputs that have large effects on controlled variables.
- Choose inputs that rapidly affect the controlled variables.
- The manipulated variables should affect the controlled variables directly, rather than indirectly.
- Avoid recycling of disturbances.

Measured Variables:

- Reliable, accurate measurements are essential for good control
- Select measurement points that have an adequate degree of sensitivity
- Select measurement points that minimize time delays and time constants.

Other terms related to this are:

Set Point:
Desired or target value of an essential measured output variable.

Error:

It is the deviation of process variable from the set point.

Error = Set point – process variable

State variable:

These are the variables that describes the nature of a process.

The fundamental quantity like mass, energy cannot be directly measured and are measured with the help of temperature, pressure composition, flow rate etc. are called state variable.

Controller:

It is a dynamic system to control the desired variable by comparing with required set point.

Dead time:

It is the amount of time taken for a process to start changing its behaviour after disturbance in the system.

Control Lag:

Control lag is the time for the process-control loop to make necessary adjustments to the final control element.

Identification of process and plant constraints:

The objectives and constraints of the process must be identified before process control actions can be performed.

The process objectives include the type, quantity, and quality of the product that is to be produced from the process. The economic objectives, such as the desired levels of raw material usage, costs of energy, costs of reactants, and price of products, should also be identified.

The process constraints include three different categories: operational, safety, and environmental limitations.

- Operational constraints refer to the limits of the equipment used in the process. For instance, a liquid storage tank can only hold a certain volume.
- Safety constraints describe the limits when the people or the equipment may be in danger. An example would be a pressure limitation on a reactor, which if exceeded, could result in an explosion.
- Environmental constraints limit how the process can affect the immediate surroundings. For example, the amount of harmful chemicals that can be released before damage is done to nearby water supplies.

All of these constraints should be mentioned to build a robust control system. Careful reading of the information provided to you by the customer, management, and government is required in order to properly identify each constraint and objective. Often times, the process objectives will be very clearly laid out by the needs of the customer or management.

Operational constraints, or the limitations of the equipment being used, must be researched for each piece of equipment used in the process. Generally, by satisfying the operational constraints a good portion of safety constraints are satisfied as well, but additional safety constraints may exist and must be investigated by researching company policy and governmental regulations. Environmental regulations also have to be researched through resources such as the EPA and Clean Air Act. Satisfying the economic aspect is largely determined by manipulating additional variables after all other constraints and objectives have been met.

Module-II

Control System Design:

The methodology can be described as follows:

- **Understand the process:**

Before attempting to control a process, it is necessary to understand how the process works and what it does.

- **Identify the operating parameters:**

Once the process is well understood, operating parameters such as temperatures, pressures, flow rates, and other variables specific to the process must be identified for its control.

- **Identify the hazardous conditions:**

In order to maintain a safe and hazard-free facility, variables that may cause safety concerns must be identified and may require additional control.

- **Identify the measurables:**

It is important to identify the measurables that correspond with the operating parameters in order to control the process. Measurables for process systems are temperature, pressure, flow rate, pH, humidity, level, concentration, viscosity, conductivity, turbidity etc.

- **Identify the points of measurement:**

Once the measurables are identified, it is important locate where they will be measured so that the system can be accurately controlled.

- **Select measurement methods:**

Selecting the proper type of measurement device specific to the process will ensure that the most accurate, stable, and cost-effective method is chosen. There are several different signal types that can detect different things. These signal types include electric, pneumatic, light, radio waves etc.

- **Select control method:**

In order to control the operating parameters, the proper control method is vital to control the process effectively. On/off is one control method and the other is continuous control. Continuous control involves Proportional (P), Integral (I), and Derivative (D) methods or some combination of those three.

- **Select control system:**

Choosing between a local or distributed control system that fits well with the process effects both the cost and efficacy of the overall control.

- **Set control limits:**

Understanding the operating parameters allows the ability to define the limits of the measurable parameters in the control system.

- **Define control logic:**

Choosing between feed-forward, feed-backward, cascade, ratio, or other control logic is a necessary decision based on the specific design and safety parameters of the system.

- **Create a redundancy system:**

Even the best control system will have failure points; therefore, it is important to design a redundancy system to avoid catastrophic failures by having back-up controls in place.

- **Define a fail-safe:**

Fail-safes allow a system to return to a safe state after a breakdown of the control. This fail-safe allows the process to avoid hazardous conditions that may otherwise occur.

- **Set lead/lag criteria:**

Depending on the control logic used in the process, there may be lag times associated with the measurement of the operating parameters. Setting lead/lag times compensates for this effect and allow for accurate control.

- **Investigate effects of changes before/after:**

By investigating changes made by implementing the control system, unforeseen problems can be identified and corrected before they create hazardous conditions in the facility.

- **Integrate and test with other systems:**

The proper integration of a new control system with existing process systems avoids conflicts between multiple systems.

Nature of process disturbances:

Disturbances are the process variables that affect the controlled variables but cannot be manipulated. Disturbances generally are related to changes in the operating environment of the process: for example, its feed conditions or ambient temperature. Some disturbance variables can be measured on-line, but many cannot.

Some natures of disturbances are:

- There are three classes of disturbance that enter control loops from the outside: setpoint changes, load variations and noise.
- In case of feedback control disturbances are not measured but in case of feed forward controller disturbances are measured.

Process response:

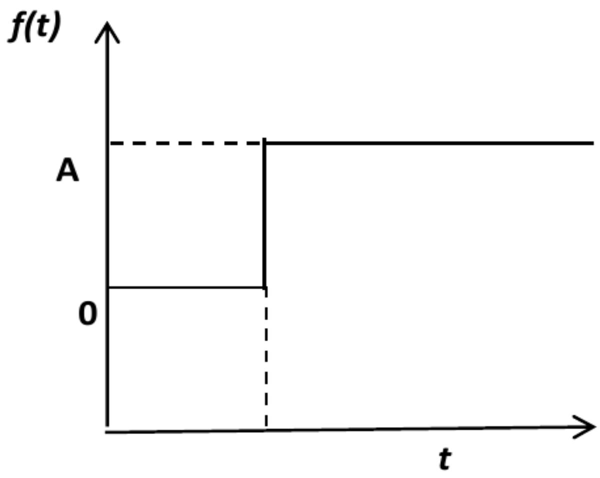
Different process responses are described as follows:

a) Step function:

One characteristic of industrial processes is that they can be subjected to sudden and sustained input changes; for example, a reactor feedstock may be changed quickly from one supply to another, causing a corresponding change in important input variables such as feed concentration and feed temperature. Such a change can be approximated by the step change

$$f(t) = \begin{cases} 0 & for\ t < 0 \\ A & for\ t \geq 0 \end{cases}$$

where zero time, as noted earlier, is taken to be the time at which the sudden change of magnitude A occurs. Note that f(t) is defined as a deviation variable i.e. the change from the normal steady state. Example: Opening of a valve to a magnitude of A.



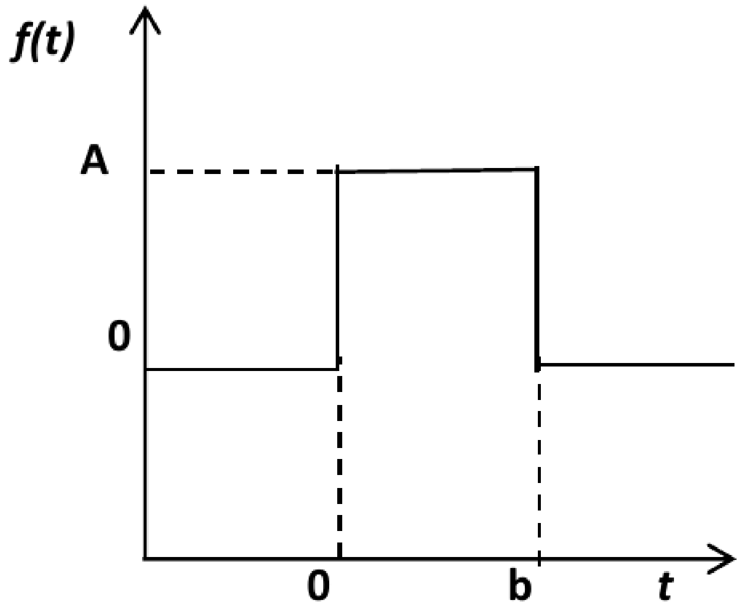
(Step function)

The Laplace transform of a step of magnitude a is = A/s

b) Pulse function:

When a disturbance is repeated at regular intervals it is described as a pulse function. It may be described as two equal functions of magnitude A operating in opposite directions. For example, processes sometimes are subjected to a sudden step change and then returns to its original value. Suppose that a feed to a tank is shut off for a certain period of time and started again. We might approximate this type of input change as a rectangular pulse.

$$f(t) = \begin{cases} 0 & for\ t < 0 \\ A & for\ 0 < t < b \\ 0 & for\ t > b \end{cases}$$



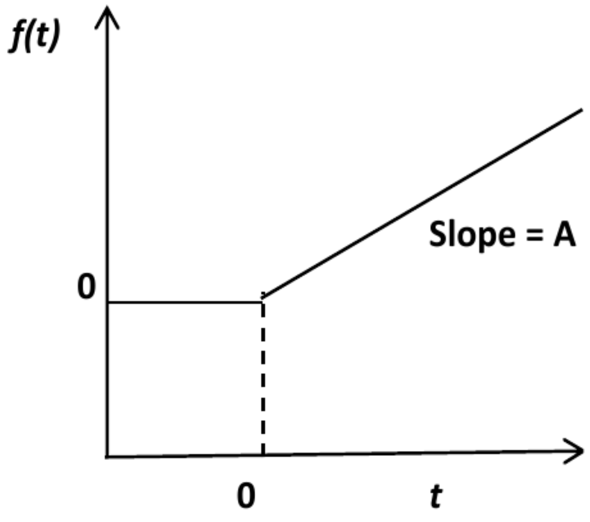
(Pulse function)

c) Ramp function:

Industrial processes often are subjected to inputs that drift i.e. they gradually change upward or downward for some period of time with a roughly constant slope. For example, ambient conditions (air temperature and relative humidity) can change slowly during the day so that the plant cooling tower temperature also changes slowly. Set points are sometimes ramped from one value to another rather than making a step change. We can approximate such a gradual change in an input variable by means of the ramp function:

$$f(t) = \begin{cases} 0 & for\ t < 0 \\ At & for\ t \geq 0 \end{cases}$$

The Laplace transform of a step of magnitude a is = A/s^2

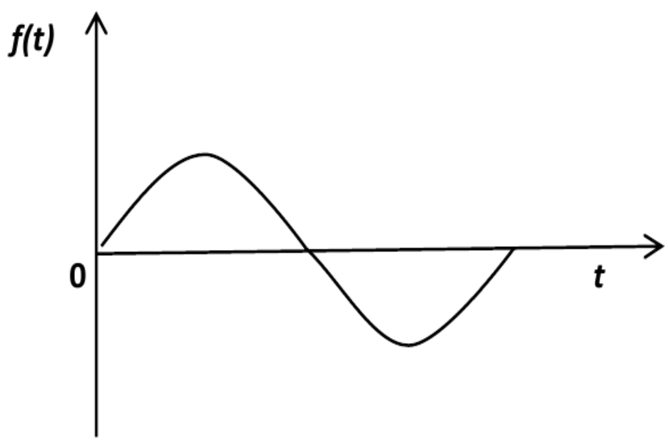


(Ramp function)

d) Sinusoidal function:

Processes are also subjected to inputs that vary periodically. As an example, the drift in cooling water temperature discussed earlier can often be closely tied to diurnal (day-to-night-to-day) fluctuations in ambient conditions. Cyclic process changes within a 24-h period often are caused by variations in cooling water temperature that can be approximated as a sinusoidal function:

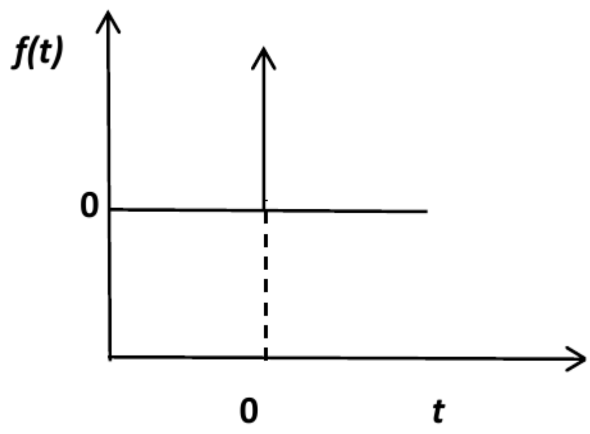
$$f(t) = \begin{cases} 0 & for\ t < 0 \\ A\ sin\omega t & for\ t \geq 0 \end{cases}$$



(Sinusoidal function)

e) Impulse function:

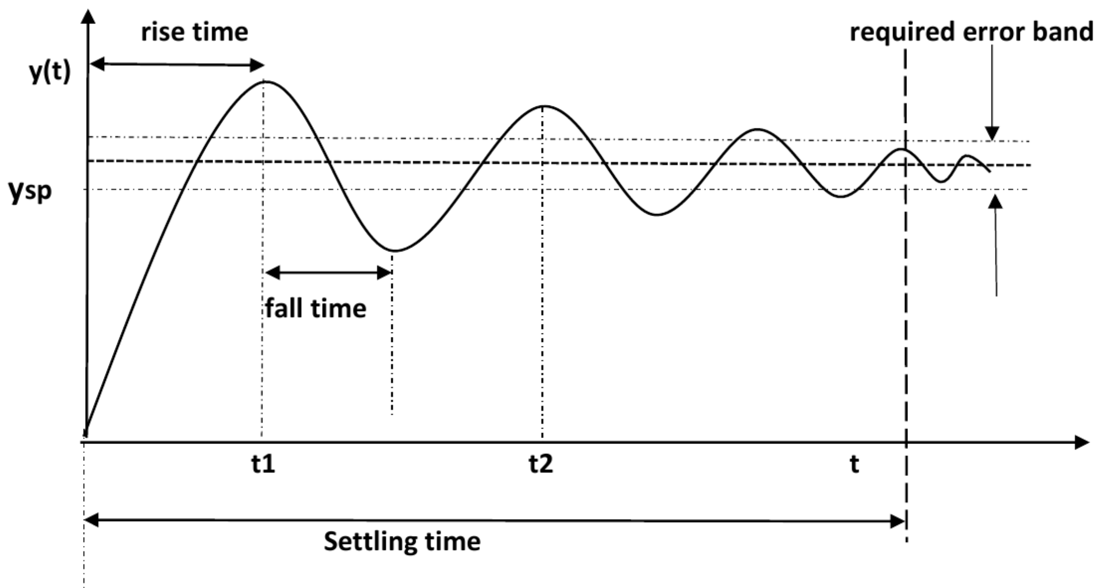
The unit impulse function has the simplest Laplace transform, L[f(s)] = 1. However, exact impulse functions are not encountered in normal plant operations. To obtain an impulse input, it is necessary to inject a finite amount of energy or material into a process in an infinitesimal length of time, which is not possible. However, this type of input can be approximated through the injection of a reagent into the process for an infinitesimal length of time.



(Impulse function)

Time domain specifications:

The transient response of a practical control system often exhibits damped oscillations before reaching a steady state. In specifying the transient-response characteristics of a control system to a unit-step input, it is common to name the following:



- **Rise Time:**

The rise time is the time required for the response to rise from low value to high value i.e. from 10% to 90% or 0% to 100%.

- **Fall time:**

The fall time is the time taken by a response to change from high value to low value.

- **Overshoot:**

This is a case of occurrence of a response exceeding the final value of the response.

- **Peak Time:**

The peak time is the time required for the response to reach the first peak of the overshoot.

- **Settling Time:**

The settling time is the time required for the response curve to reach and stay within a specified error band.

- **Decay ratio:**

It is the ratio between the response at two successive peaks.

Problems related to response determination:

Q. Solve the following first order differential equation by the use of Laplace transforms.

$$\boldsymbol{\frac{dx}{dt} + 2x = 1}$$

Based on the condition x(0) = 0.

Ans:

Step 1:

Taking the Laplace transform of the given equation we get:

$$\mathrm{s.X(s)} + \mathrm{2.X(s)} = \frac{1}{s}$$

or

$$\mathrm{(s+2).X(s)} = \frac{1}{s}$$

Using the theory of partial fractions, the above can be split as:

$$\mathrm{X(s)} = \frac{1}{s(s+2)} = \frac{A}{s} + \frac{B}{(s+2)}$$

or 1 = A.(s+2) + B.s

where A and B are constants.

Step 2:

The problem now resolves to determining A and B.

Setting s =0, A can be determined as A = 1/2

And setting s= -2, B can be determined as B = -1/2

Putting these values value of X(s) can be written as:

$$\mathrm{X(s)} = \frac{1}{2s} - \frac{1}{2(s+2)}$$

Now taking the inverse of this we can find x(t)

$$x(t) = \frac{1}{2} - \frac{1}{2}\, e^{-2t}$$

Q. Determine the response to a unit step function and a unit ramp function applied to a process defined as:

$$\mathbf{5.\frac{dy}{dx} + 2y = 3f}$$

Ans:

Taking the L transform

$$5.\mathrm{s.\,Y(s)} + 2.\,\mathrm{Y(s)} = 3.\,F(s)$$

Or $\mathrm{Y(s)} = \frac{3}{2+5s}\, F(s)$

Case-I:

For a unit step function:

F(s) = 1/s

Hence, $Y(s) = \frac{3}{(2+5s).s} = \frac{A}{(2+5s)} + \frac{B}{s}$

Or 3 = A.s + B. (2+ 5s)

Setting s=0, B can be determined as B = 3/2

And setting s= -2/5, A can be determined as A = -15/2

Putting these values value of Y(s) can be written as:

$$Y(s) = \frac{-15}{2(2+5s)} + \frac{3}{2s}$$

Or y(t) can be determined as

$$y(t) = \frac{3}{2} - \frac{15}{10}\ e^{-2t/5}$$

Case-II:

For a unit ramp function:

F(s) = 1/s^2

Hence, $Y(s) = \frac{3}{(2+5s).s^2} = \frac{A}{(2+5s)} + \frac{B}{s^2}$

Or 3 = A. s^2 + B. (2+5s)

Setting s=0, B can be determined as B = 3/2

And setting s= -2/5, A can be determined as A = -75/4

Putting these values value of Y(s) can be written as:

$$Y(s) = \frac{-75}{4(2+5s)} + \frac{3}{2s^2}$$

Or y(t) can be determined as

$$y(t) = \frac{3t}{4} - \frac{75}{20}\ e^{-2t/5}$$

MODULE-III

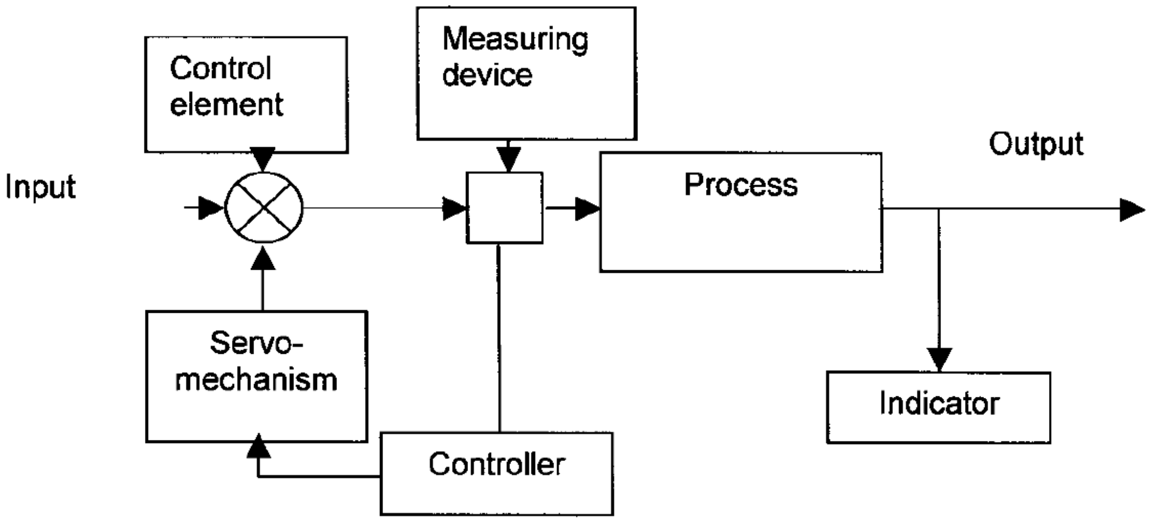
Control Actions:

The control system can be classified into two basic structure:

- Feed Forward control
- Feedback control

Feed Forward Control:

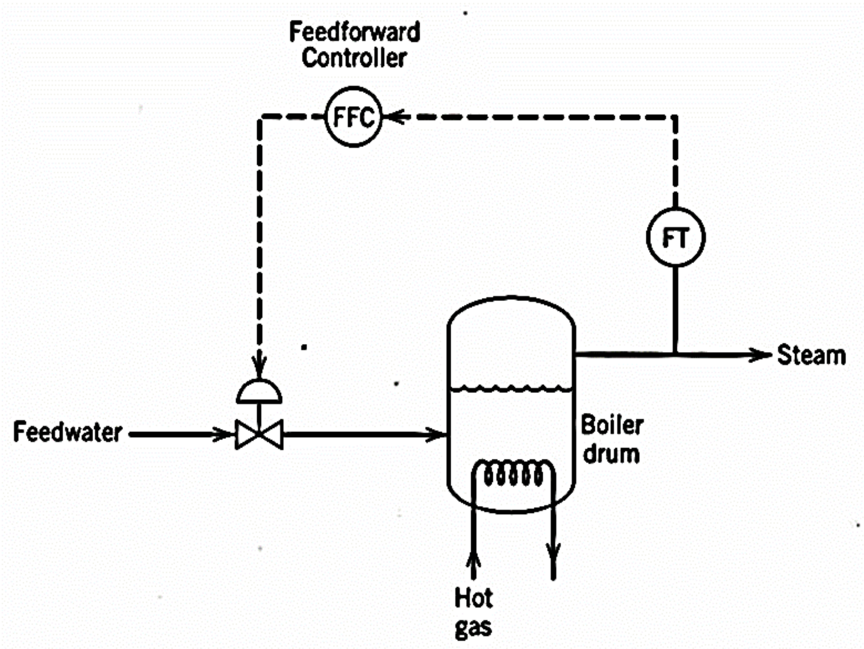
A feed forward controller detects the disturbances directly and takes an appropriate control action in order to eliminate its effect on the process output.



(Feed Forward Control)

In practical applications, feedforward control is normally used in combination with feedback control. Feedforward control is used to reduce the effects of measurable disturbances, while feedback trim compensates for inaccuracies in the process model, measurement error, and unmeasured disturbances.

Example: Liquid level control of boiler drum



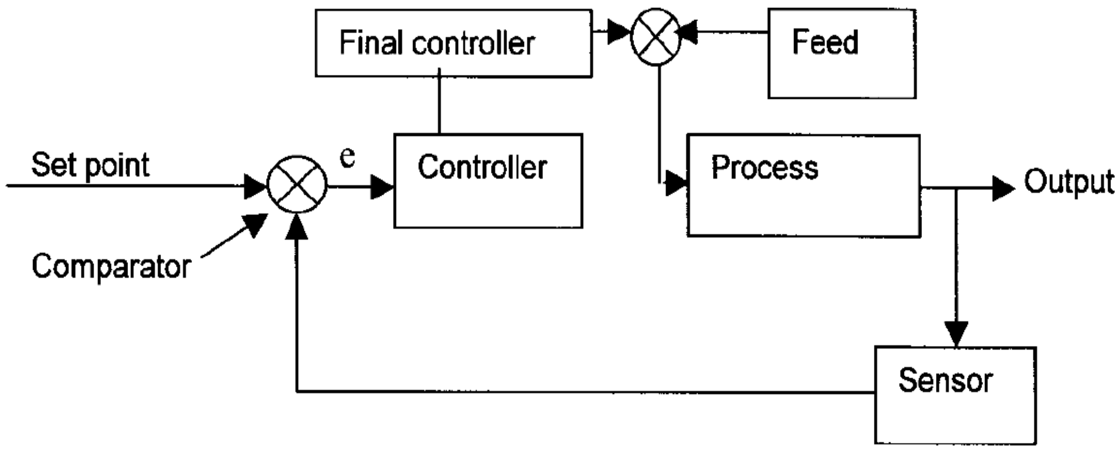
(boiler drum)

Feed forward control has several disadvantages:

- The disturbance variables must be measured on-line. In many applications, this is not feasible.
- To make effective use of feedforward control, at least a crude process model should be available. In particular, we need to know how the controlled variable responds to changes in both the disturbance and manipulated variables. The quality of feedforward control depends on the accuracy of the process model.
- Ideal feedforward controllers that are theoretically capable of achieving perfect control may not be physically realizable. Fortunately, practical approximations of these ideal controllers often provide very effective control.

Feedback control:

Here the output from a process is monitored continuously by a sensor, when the output changes the sensor detects the change and send the signals to a comparator which compare the signal with the set point for normal steady state operation. It then estimates the error or deviation from the mean. The error signal is passed on to the controller which compares the signal with the true set point and send a signal to an operating device to reduce the error to zero.



(Feedback control)

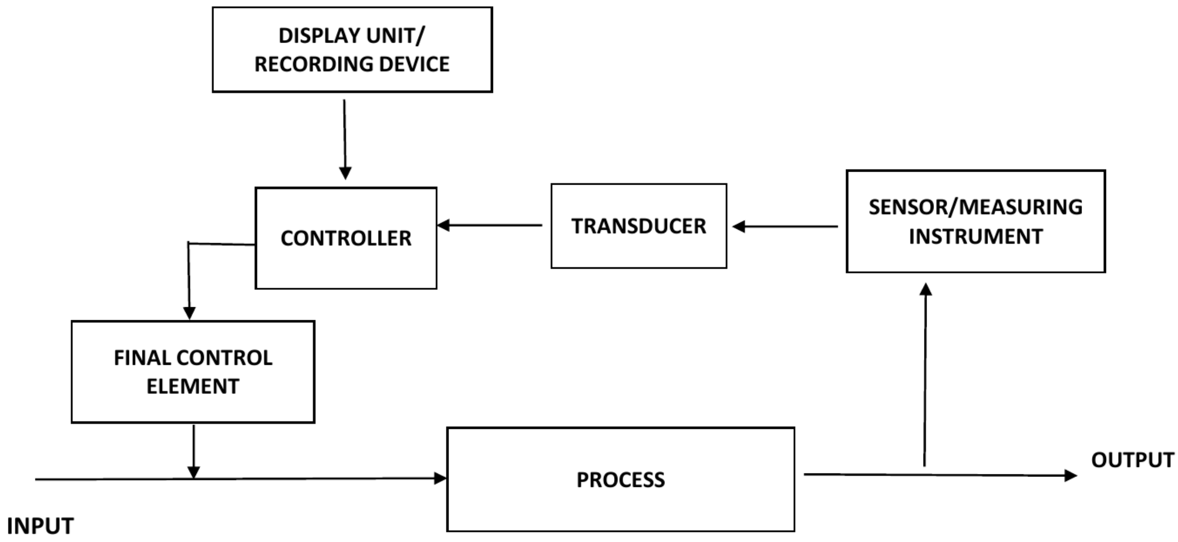
Disadvantages:

- No corrective action is taken until after a deviation in the controlled variable occurs. Thus, perfect control, where the controlled variable does not deviate from the set point during disturbance or set-point changes, is theoretically impossible.
- Feedback control does not provide predictive control action to compensate for the effects of known or measurable disturbances.
- It may not be satisfactory for processes with large time constants and/or long-time delays. If large and frequent disturbances occur, the process may operate continuously in a transient state and never attain the desired steady state.
- In some situations, the controlled variable cannot be measured on-line, and, consequently, feedback control is not feasible.

Construction of a feedback control system:

A feedback control system has several parts as below:

a. **Process:**
   It is the system where a physical or chemical operation occurs. Example: heating tank



(A feedback control system)

b. Measured Instrument/ Sensor:

Use to measure the disturbances, controlled output variables or secondary output variables and transmit.

Variable	Sensor
Temperature	Thermocouple, resistance thermometer
Pressure	Diaphragm element
Flow	Venturi meter
Liquid level	Differential pressure cell
Composition	Chromatographic analyzer

c. Transducer:

Convert the measurement to physical quantity like voltage or current which can be transmitted easily.

d. Transmission lines:

Transmission lines are used to carry the measured signal from measuring device to the controller.

e. **Amplifier:**

In case there is a weak signal from the measuring device amplifiers are used to raise the level of signal.

f. **Controller:**

It receives the measured signal from sensor and take the necessary action after comparing with the desired value.

g. **Final control element:**

FCE implicate the control action physically at the required position.

Example: control valve, variable speed pump etc.

h. **Display and Recording Device:**

Used to visualize the plant behaviour and record it.

Example: video display, PLC etc.

Control Mode:

There are two modes of control action:

- Discontinuous control mode
- Continuous controller

Discontinuous control mode:

In Discontinuous mode the controller command intimates a discontinuous change in in the controller parameters.

Different types of discontinuous modes

- Two position mode
- Multi position mode
- Floating control mode

Continuous mode:

In continuous mode, smooth variation of the control parameters is possible.

Different types of continuous modes

- Proportional controller (P)
- Integral controller (I)
- Derivative controller (D)

Composite controller modes:

Composite controller modes combine the continuous control modes.

- Proportional – Integral (PI)
- Proportional – Derivative (PD)
- Proportional – Integral – Derivative (PID)

Control actions

The error that result from the measurement of the controlled variable may be positive or negative. Types of control action

- Direct action
- Reverse action

Direct action:

A controller is said to be operated with direct action when an increasing signal of input results the increase of the output signal.

Example: level control system: If the level rises (controlled variable increases) the control output should increase to open the valve more to keep the level under control.

Reverse action

A control is said to be operating with reverse action when an increasing value of the controlled variable causes a decreasing value of the controller output.

Example a simple temperature control of furnace with fuel as heat energy. If the temperature increases, the control output should decrease to close the valve for decreasing the fuel input to bring the temperature under control.

ON - OFF Controller:

Two position control is a position type of a controller action in which manipulated variable is quickly changed to either maximum (or) minimum value depending upon whether the controlled variable is greater or less than the set point.

Two position control mode is also called ON – OFF control mode.

$$C(t) = \begin{cases} C_{MAX} & if\ error \geq 0 \\ C_{MIN} & if\ error < 0 \end{cases}$$

C(t) = controller output

Example:

- For valve: fully open to fully closed
- For digital computer: 0% to 100%
- For current based electronic controller: 4mA to 20mA
- For pneumatic controller: 3 psi to 15 psi

Applications:

- Liquid bath temperature control
- Level control
- Room heating System
- Air conditioners

Proportional control:

A proportional control system is a type of linear feedback control system where the control action is proportional to the error i.e. higher the error higher the control action and vice-versa.

In this control mode a linear relationship exists between the controller output and error.

$$\mathbf{C(t) = k_c\, e(t) + C_s}$$

C(t) = Control signal

k_c = proportional gain between error and controller output

C_s = controller output with no error

e(t) = error

Proportional controller is also called as gain controller.

Bias signal:

It is the value of the control signal at zero error.

Proportional Band (PB):

It is defined as the range of error to cover 0% to 100% controlled output.

PB can be expressed by the equation

$$PB = 100/ k_c$$

k_c = proportional gain

PB = proportional band

PB is dependent on gain. High gain means large response to an error.

Offset error:

It is the steady state deviation of the controlled variable from the set point. It is a permanent residual error in the operating point of the controlled variable when load change occurs. It cannot be eliminated in proportional controller as no practical error is there.

Integral controller:

For integral control action, the controller output depends on the integral of the error signal over time.

$$C(t) = \frac{1}{\tau_I} \int_0^t e(t).dt + C_s$$

where τ_I is an adjustable parameter referred to as the integral time or reset time with units of time.

Integral controller is also called as reset controller.

Integral control action is widely used because it provides an important practical advantage, the elimination of offset.

Proportional-Integral controller (PI controller):

PI controller not only actuates on the basis of error, but also accounts for the history of all the past errors that has been encountered since the control action has started.

$$C(t) = k_c\{e(t) + \frac{1}{\tau_I} \int_0^t e(t).dt\} + C_s$$

PI controller is also called gain-reset controller.

Reset windup (Integral windup):

In PI controller, as long as the error is present controller keeps changing its output by integrating the error. When a sustained error occurs, the integral term becomes quite large and the controller output got saturated. Further build-up of integral term is called reset windup.

Reset windup is reduced by temporarily halting the integral control action whenever the controller output saturates.

Derivative Controller:

The function of derivative control action is to anticipate the future behaviour of the error signal by considering its rate of change.

The controller output is given by:

$$C(t) = \tau_D \frac{de(t)}{dt} + C_s$$

where τ_D is derivative time constant or pre-act time with units of time.

Derivative controller is also called as pre-act controller.

Proportional-Integral-Derivative Controller (PID controller):

It is the combination of the proportional, integral, and derivative control modes. PID controller not only actuates on the basis of current and past errors but also anticipates the error in immediate future.

$$C(t) = k_c \left\{ e(t) + \frac{1}{\tau_I} \int_0^t e(t).\,dt + \tau_D \frac{de(t)}{dt} \right\} + C_s$$

PID controller is also called gain-reset-pre-act controller.

Difference between feed forward and feedback control

Feed forward	Feedback
Take action before the process feels disturbances	Not require to measure any disturbances, Takes action after the process output
Good for system with large dead time	Not applicable for large dead time
Does not affect the stability of the process	May affect the stability of the process
Sensitive to variation of process parameters	Insensitive to variation of process parameters
Requires a perfect model of process	Can adjust modelling errors

Tuning of feedback controllers:

Tuning is the process to get best possible closed loop performance.

Tuning parameters are:

- For P-only controller: k_c
- For PI controller: k_c and τ_I
- For PID controller: k_c, τ_I and τ_D

There are several qualitative tuning criteria as:

- Return to desired level operation as soon as possible.
- Keep the maximum deviation as small as possible.

There are two general approaches for tuning of a controller:

Using simple criteria:

Tuning can be done by using simple criteria such as

- one quarter decay ratio
- minimum settling time
- minimum largest error
- minimum rise time

Using time integral performance criteria:

Different time integral criterion used in selecting the control parameters are ISE, IAE and ITAE.

Integral of the square error (ISE):

$$\text{ISE} = \int_0^\infty e^2(t)dt$$

Where e = error

ISE strongly suppresses large errors.

Integral of the absolute value of the error (IAE):

$$\text{IAE} = \int_0^\infty |e(t)|dt$$

IAE strongly suppresses small errors.

Integral of the time-weighted absolute error (ITAE):

$$\text{ITAE} = \int_0^\infty t|e(t)|dt$$

ITAE strongly suppresses errors that persist for long times.

Open loop and Closed loop controller:

For an open loop controller, the process variable is not compared and action is not taken in response to feedback. For a closed loop controller, the process variable is measured, compared to a set value and action is taken.

Multiple input control:

When more than one input and output exist in a process, several control configurations are possible depending on which output is controlled by manipulating which input. In order to arrive at the best possible configuration, one need to consider the following:

- process variables are needed to be controlled
- Outputs to be measured (primary measurements/secondary measurements)
- Inputs to be manipulated
- Possible control configurations (input/output mapping) and best among them

It is clear that in order to determine a system completely, its Degree of Freedom (DoF) should be equal to zero. There are two sources of additional specifications/equations that would reduce the DoF to zero, viz. control system and its surroundings. The surrounding refers to everything outside the domain of closed loop system which has the capability of influencing the operating conditions. The process disturbances and few externally specified inputs fall under this category. Remaining equations are provided by the control system that imposes certain relationships between outputs to be controlled and the inputs to be manipulated. These relationships are nothing but the controller equations.

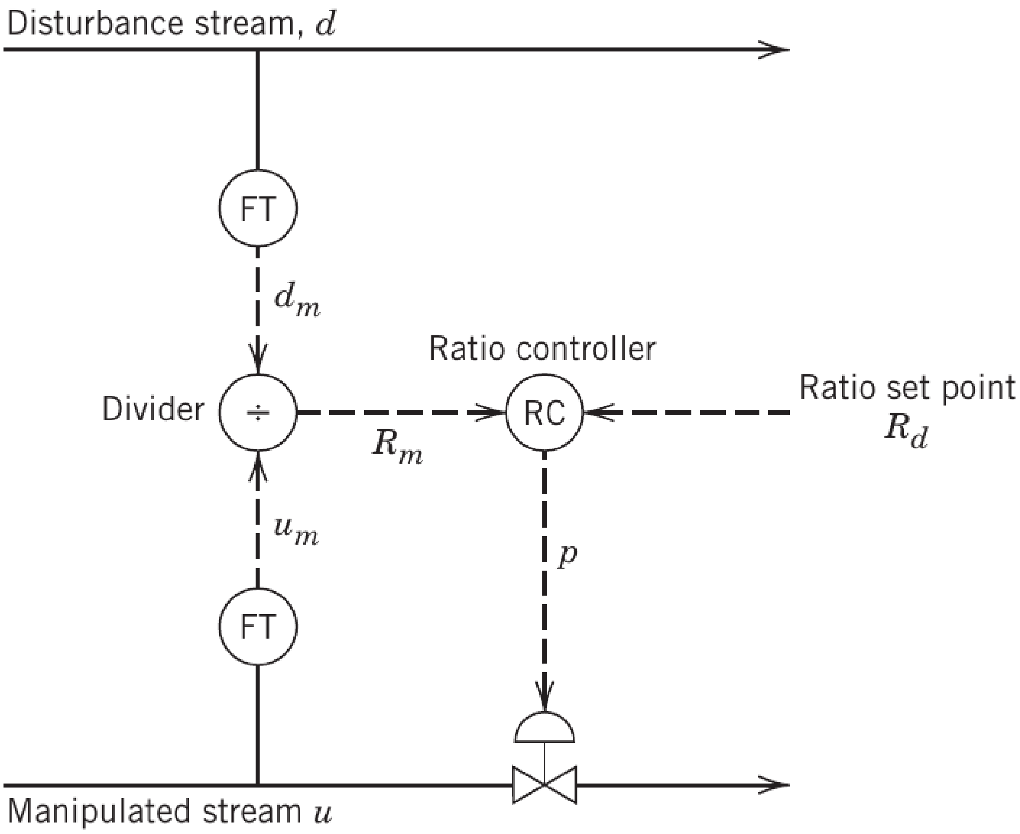
Ratio control:

Ratio control is a special type of feedforward control that has had widespread application in the process industries. Its objective is to maintain the ratio of two process variables at a specified value. The two variables are usually flow rates, a manipulated variable u and a disturbance variable d.

Thus, the ratio R = u/d is controlled rather than the individual variables.

Typical applications of ratio control include

- ➢ specifying the relative amounts of components in blending operations,
- ➢ maintaining a stoichiometric ratio of reactants to a reactor,
- ➢ keeping a specified reflux ratio for a distillation column,
- ➢ holding the fuel-air ratio to a furnace at the optimum value.

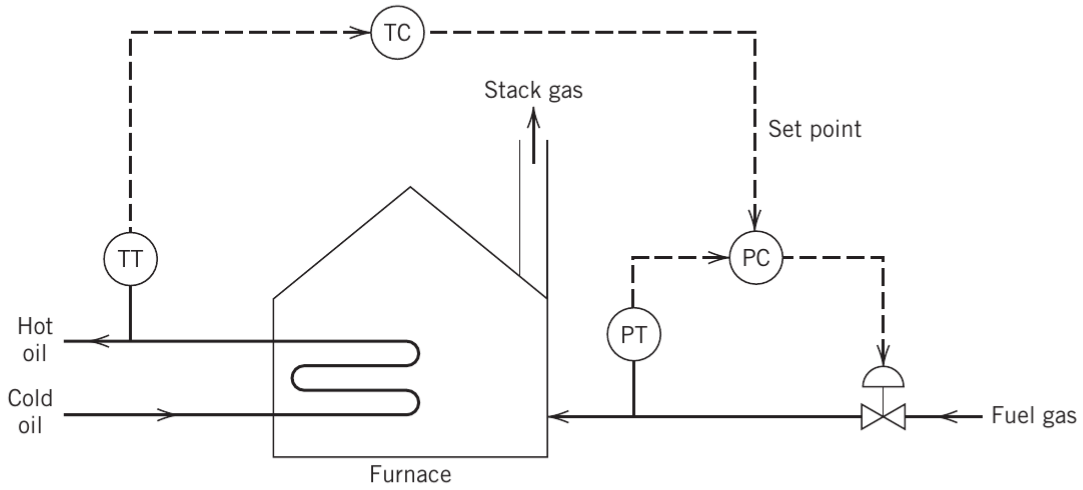


(Ratio controller)

Cascade control:

A disadvantage of conventional feedback control is that corrective action for disturbances does not begin until after the controlled variable deviates from the set point. Feedforward control offers large improvements over feedback control for processes that have large time constants or time delays. However, feedforward control requires that the disturbances be measured explicitly, and that a steady-state or dynamic model be available to calculate the controller output.

An alternative approach that can significantly improve the dynamic response to disturbances employs a secondary measured variable and a secondary feedback controller. The secondary measured variable is located so that it recognizes the upset condition sooner than the controlled variable, but possible disturbances are not necessarily measured. This approach, called cascade control, is useful when the disturbances are associated with the manipulated variable or when the final control element exhibits nonlinear behaviour.



(A furnace temperature control scheme using cascade control)

The cascade control loop structure has two distinguishing features:

- The output signal of the primary controller serves as the set point for the secondary controller.
- The two feedback control loops are nested, with the secondary control loop (for the secondary controller) located inside the primary control loop (for the primary controller).

The secondary controller is called master controller where as the primary controller is called a slave controller.

Process control in Mineral Processing:

The process of controlling a dynamic system is complicated especially in mineral processing systems where a number of variables are involved simultaneously. Developments towards automatic control of plant operations have been commensurate with the development of computer science and instrument technology. Its implementation has resulted in consistent plant performance with improved yield and grade of the product with less manpower.

The term "process control" therefore refers to an engineering practice that is directed to the collection of devices and equipment to control processes and systems. Computers find application in simple systems, such as single loop controllers and also in large systems as the Direct Digital Controller (DDC), Supervisory control systems, Hybrid Control Systems and Supervisory Control and Data Acquisition (SCADA) systems. Further developments in process control are supported by many secondary concepts such as computer aided Engineering (CAE).

The commonly used present system is the Distributed Control System (DCS). It is made up of three main components,

a. Data highway,
b. Operator station
c. Microprocessor-based controllers

The data highway handles information flow between components ensuring effective communication. The microprocessor controllers are responsible for effective control of the processes and are configured to handle as single or multi-loop controllers. The operator station allows the control command to be given, maintain the system data base and display the process information. The displays normally used are the group and detail displays, trend displays and alarm annunciate displays.

Basic Functions:

a. Human-machine interface (HMI):

The interaction between the automation system and the operator plays an important role in ensuring an effective operation.

b. Data acquisition and processing:

This function processes the data obtained from the sensors and sends suitable commands to the actuators. Sensors are devices that obtain information in the form of one or more physical quantities, and convert it into an electrical output signal.

c. Communication:

This function deals with communication between the control system function and other computer systems.

d. Regulatory control:

This comprises a combination of discrete and continuous control functions, which aims at stabilizing the process and keeping its operation within safe margins for the process, equipment and the workforce.

e. Process analysis:

This includes tools for modelling and analysing the process, as well as incoming flows. These functions can be used to analyse the whole process starting with the raw materials through all the process steps down to the end products.

f. Optimization:

This function seeks to improve the operational level by taking actions according to a given performance index.

g. Fault detection:

It aims at promptly detecting failures in the equipment and automation hardware and/or software.

General control strategies:

Basically, three types of control strategies are used in mineral processing circuits:

a. Regulatory
b. Supervisory
c. Optimizing

a. Regulatory:

Mostly implemented with feedback loops like stabilizing of process inputs like flow, level etc. and used PID controller. The control interval ranges from 1-10 sec.

b. Supervisory:

It calculates the set points for regulation of operational objectives, i.e. maximum output with maximum grade. These control strategies mostly use cascade PID loop. The control interval ranges from 20 sec- 2 min.

c. Optimizing:

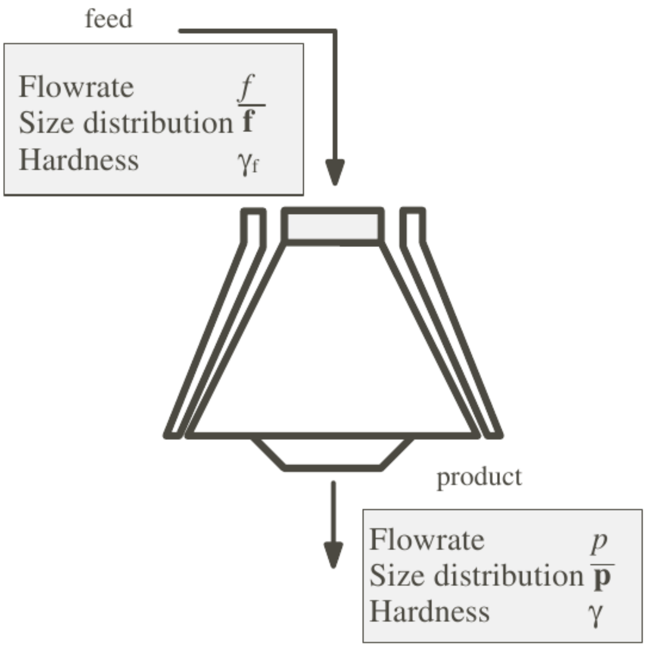
It calculates operating objectives for the supervisory strategies based on economic objective. This control strategy uses costly analytical equipment and process models. The control interval ranges from few minutes to 1 hour.

Crushing circuit:

The control of any crushing operations starts with the control of the feed system.

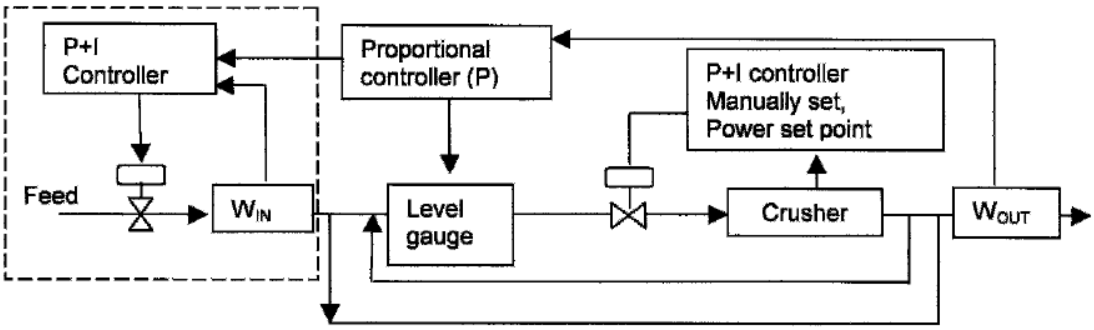
Lynch has summarized the disturbances in a crusher as:

- ore properties (size and hardness)
- ore feed rate
- crusher settings (close and open settings) alterations due to wear and tear
- surge in feed load and plant power draw



(A cone crusher and its main variables)

In this control loops of a gold crushing plant, two regulatory control loops and a supervisory control loop are there. The function of one regulatory loop (shown within dotted lines) is to control the feed tonnage on the feeder conveyor and the other to regulate the crusher power which in turn regulates the feed. The supervisory loop is a cascade loop which deals with any imbalance between the two regulatory loops through level changes in the feed hopper.



(Control loop of gold crushing plant)

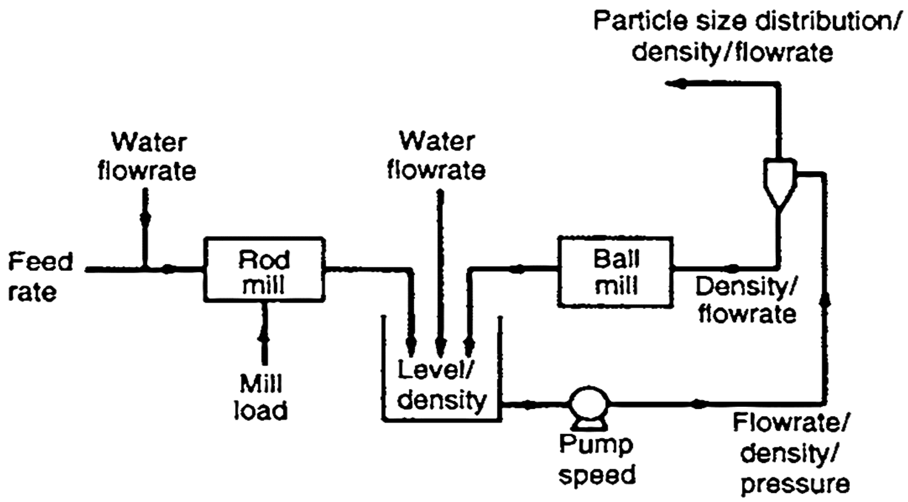
Grinding circuit:

In implementing instrumentation and process control for grinding circuits the control objective must first be defined, which may be:

- to maintain a constant product size distribution at maximum throughput
- to maintain a constant feed rate within a limited range of product size
- to maximise production per unit time in conjunction with downstream circuit performance (e.g. flotation recovery).

To achieve these objectives an attempt is made to stabilize the operation by principally controlling the process variables. The main disturbances in a grinding circuit are;

- change in ore characteristics (ore feed rate, grindability, feed particle size distribution, mineral composition and mineral characteristics like abrasiveness, hardness),
- changes in mill operating parameters like variation of input flow rate of material like surging of feed caused by pumps and level of mill discharge sump.



(Grinding circuit control)

The mill control strategy has to compensate for these variations and minimize any disturbances to the hydro-cyclone that is usually in closed circuit.

The simplest arrangement is to setup several control loops like:

a. Control of water/solid ratio in the feed slurry,
b. Sump level control,
c. Product size distribution control
d. Control of circulating load.

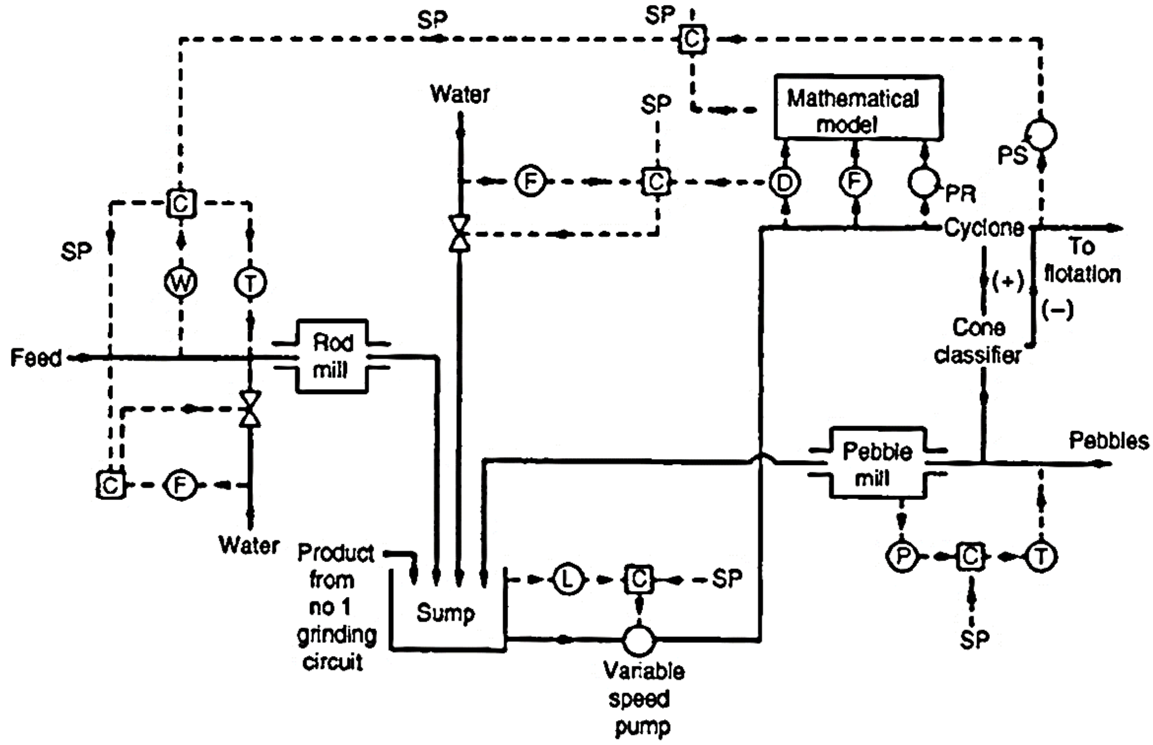
These parameters can be controlled as:

Control Variable	Controlled Variable
Ore feed rate	water/solid ratio in the feed slurry
Pump speed	Sump level
Water addition to sump	Product size distribution
Ore feed rate	circulating load

Presently most mills use centrifugal pumps for discharging from the sump. This helps to counter surges and other problems related to pumping. For feed control the most likely option is to use a feed forward control while for controlling the hopper level and mill speed and other loops the PI or PID controller is used. The control action should be fast enough to prevent the sump from overflowing or drying out. This can be attained by a cascade control system. The set point of the controller is determined from the level control loop. This type of control promotes stability.

The flowsheet and instrumentation for a grinding circuit are shown below. The control concentrates on keeping the particle size constant by regulating the crushed ore feed to the rod mill, and on stabilising the cyclone feed density by regulating the water addition to the cyclone pump sump.

- The rod mill feed is measured by means of an electric belt weigher, and is kept constant by regulating the speed of the belt feeder.
- Water addition to the mill is controlled according to the feed rate set-point to maintain a constant slurry density.
- The rod mill discharge is fed to a sump where it joins the discharge from another grinding circuit. The sump level is monitored by means of a pressure transducer and controlled by a variable speed pump, the slurry density being stabilised by water addition to the sump.
- The slurry is pumped to a hydro-cyclone, the flow rate and density in the feed-line being monitored. The cyclone underflow is fed to a cone classifier, the overflow from this joining the cyclone overflow and providing feed to the flotation plant. The particle size was originally inferred from the cyclone feed data by means of an empirical mathematical model, but was later measured directly by an online particle analyser, the particle size being controlled at 60% - 75µm. The coarse product from the cone classifier was fed to a pebble mill, the pebble feed being controlled according to the power consumed.



(A detailed grinding circuit control)

F = Flow rate; W = Weight (belt scale) T = Thyristor control; D = Density; PR = Pressure;

PS = Particle size; P = Power; L = Level; SP = Set-point; C = Controller

Flotation circuit:

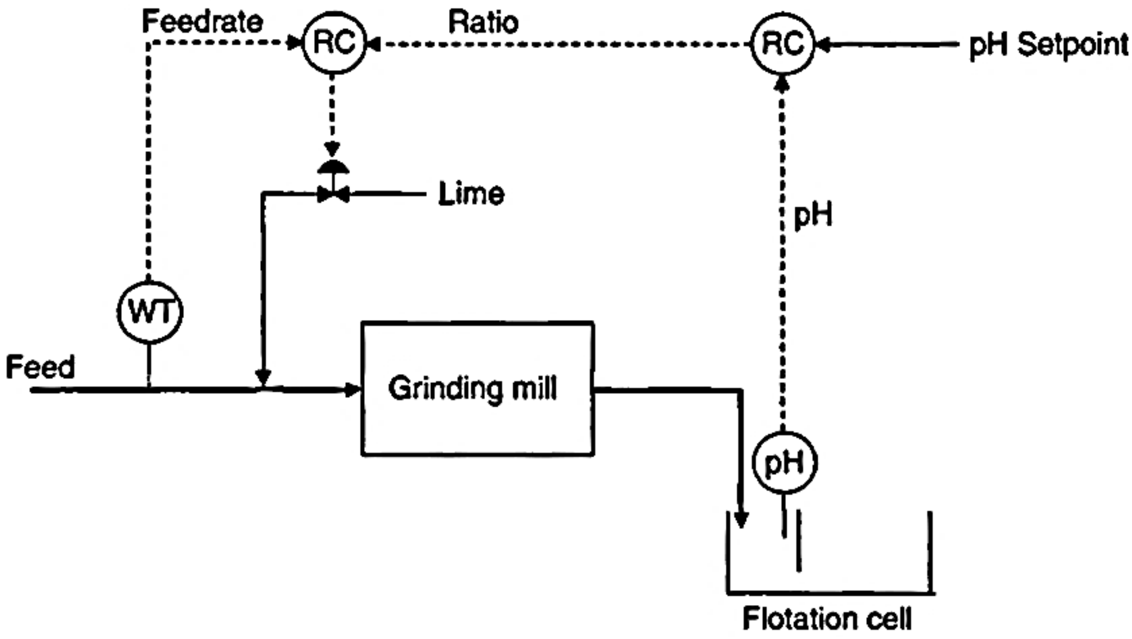
A flotation control system consists of various subsystems, some of which may be manually controlled, while others may have computer- controlled loops, but all contributing to the overall control objective. The aim should be to improve the metallurgical efficiency, i.e. to produce the best possible grade-recovery curve, and to stabilise the process at the concentrate grade which will produce the most economic return from the throughput, despite disturbances entering the circuit.

The variables which are manipulated are mass flows, reagent and air addition rates, pulp and froth levels, pH, and circulating loads by the control of cell-splits on selected banks.

The control objectives are:

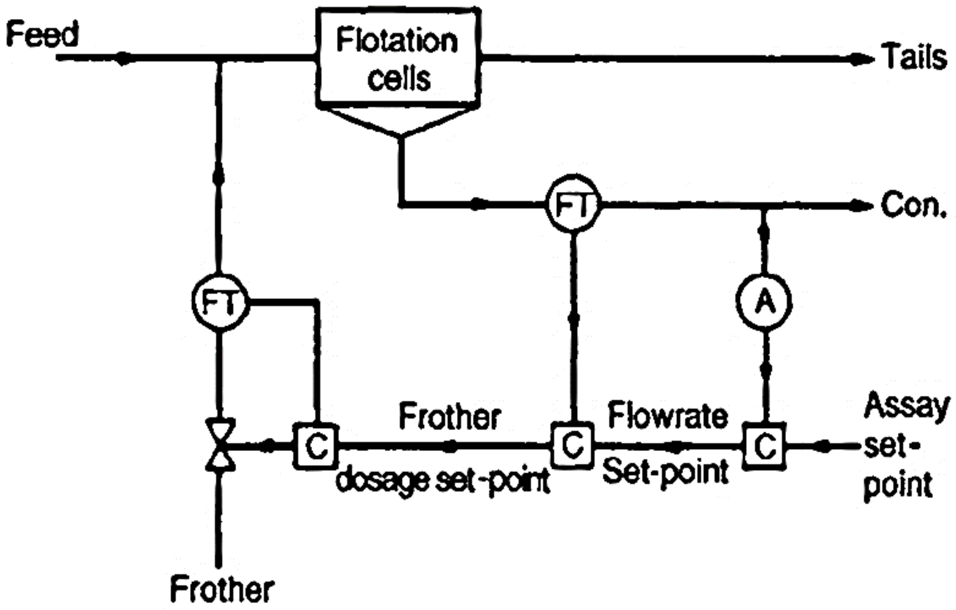
- Stabilizing control of pulp and sump levels, air flow, and reagent flows
- Control of pH, reagent ratio, pulp flow, circulating load, concentrate grade and recovery
- Maximum recovery at a target grade

Control of slurry pH is a very important requirement in many selective flotation circuits, the control loop often being independent of the others, although in some cases the set-point is varied according to changes in flotation characteristics. Lime addition is controlled by the ratio of the mass flow to the mill, and the ratio set-point is adjusted by a pH controller which measures pH early in the flotation process with an operator-determined pH set-point.



(pH control)

Control of reagent addition rate is sometimes performed by feed-forward ratio control based on a linear response to assays or tonnage of valuable metal in the flotation feed. Cascade control can also be used, where the concentrate grade controls the concentrate flow rate set-point, which in turn controls the frother addition set-point.



(Reagent control)

Control of thickener:

The control objectives of thickener are as follows:

- to obtain a clear overflow as rapidly as possible.
- To get thick underflow
- To achieve higher sedimentation rate

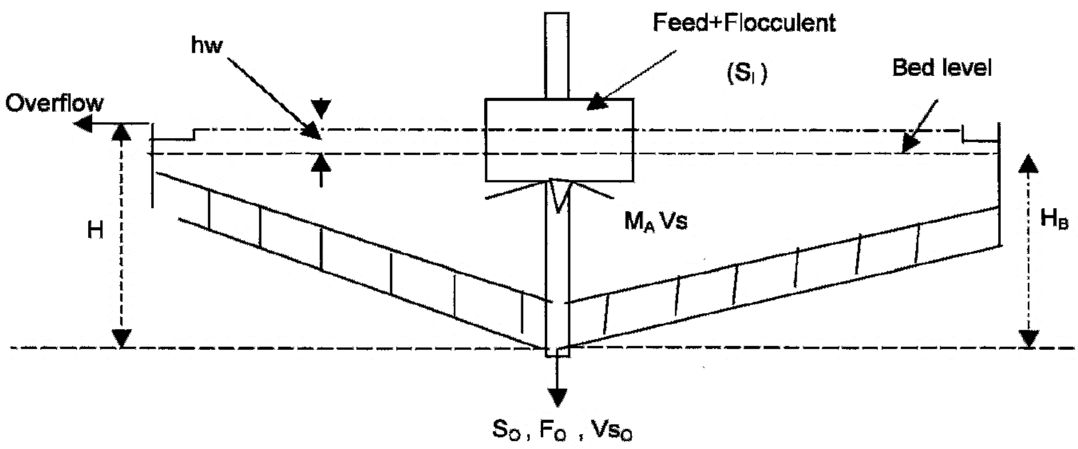
The sedimentation rate is usually accelerated by additions of flocculants. Flocculants are added in the feed pipe (or feed launder) and maximum dispersion attempted by appropriate design of its entry to the thickener tank. The choice of flocculent and its concentration vary and depends on the minerals present in the slurry, their composition and their surface characteristics. It is necessary not to have too much turbulence at the entry point of the tank. For this purpose, the overflow level is kept sufficiently high above the feed level to ensure acceptable solid concentration in the overflow.

From a process control point of view the design parameters and major variables are:

- height of the overflow clear fluid (H_W)
- height of the bed level from discharge end (H_B)
- solids inventory (S)
- sold mass inflow (S_I)
- solids mass outflow (S_O)
- average bed solid volumetric fraction (V_S)

It can be seen that the solid inventory $S = A\ H_B\ V_S\ \rho_S$

where ρ_S is the solids density



(Schematic diagram of thickener control)

At the bed level the solids residence time, t_R will be:

$$t_R = \frac{S}{S_I}$$

The dynamic solids mass balance is:

$$\frac{dS}{dt} = S_I - S_O$$

Control Strategy:

The control of the solid contents in the overflow and underflow streams is the basis of thickener control. The average bed density (solids inventory) has to be controlled by the underflow flow rate and the flocculent additions to the slurry. To attain target overflow solids concentration the underflow density should be sufficiently high. This is obtained by longer residence time of treated slurry in thickener.

The underflow flow rate is measured by magnetic or ultrasonic flow meters.

The control scheme can now be summarized as:

Level 1: Control loops

Two main loops are placed in Level 1. The first main loop(a) is for underflow control and the second main loop(b) is for the control of flocculent flow.

At level a, the essential process measurements for underflow control are:

- rake torque with a torque meter fixed to the rakes,
- bed level by using a simple float or vertical position sensor,
- thickener bed pressure, by measuring the pulp pressure on the floor by a sensor.

At level b for flocculent loop control, measurements are chiefly flow rates of fluids by standard flow meters and power draft measurements for variable speed positive displacement pump. Other measurements at this level include:

- pump speed,
- underflow density measurement (y-ray density gauge),
- pump discharge pressure by standard pressure gauge.

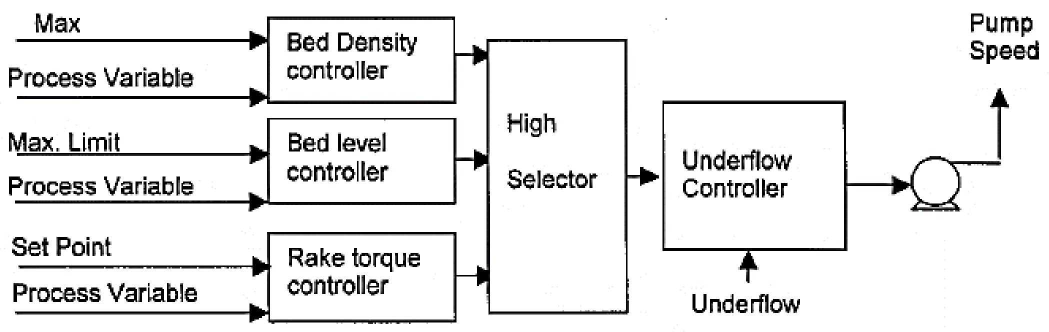
Level 2: Control loops

The aim of Level 2 is to keep the underflow bed level close to target. The set point of the bed level is therefore controlled by the bed level controller. In practice it is found that the bed level can be disturbed by high bed density which could result in high torque on the rakes. To avoid such situations the basic flow control is designed to be over-ridden. This is achieved by providing a high-selector that outputs the flow set point. The output from high selector or the flow controller set point has a set low limit. A safe flow is therefore maintained from the underflow. The pump that pumps the underflow is set to high and low speed limits taking signals from the output of the flow controller.

The advantage of this system is that in the event the thickener operation ceases due to say, stoppage of mill operation, and therefore feed to the thickener, the underflow pump continues to operate till the thickener is empty and chances of clogging is remote.

The pump speed controller incorporates limiting power draft so that the pump does not trip at high power.

For controlling the flocculent flow signals are taken from the bed density controller. Controlling the flocculent flow is difficult by this method as it takes time for the flocculent to properly mix with the rest of the inventory. The speed of response varies with the rate of change of bed density.



Level 3: Control loops

Level 3 control involves optimisation of thickener operation (and pipe lines). This includes cost function based on:

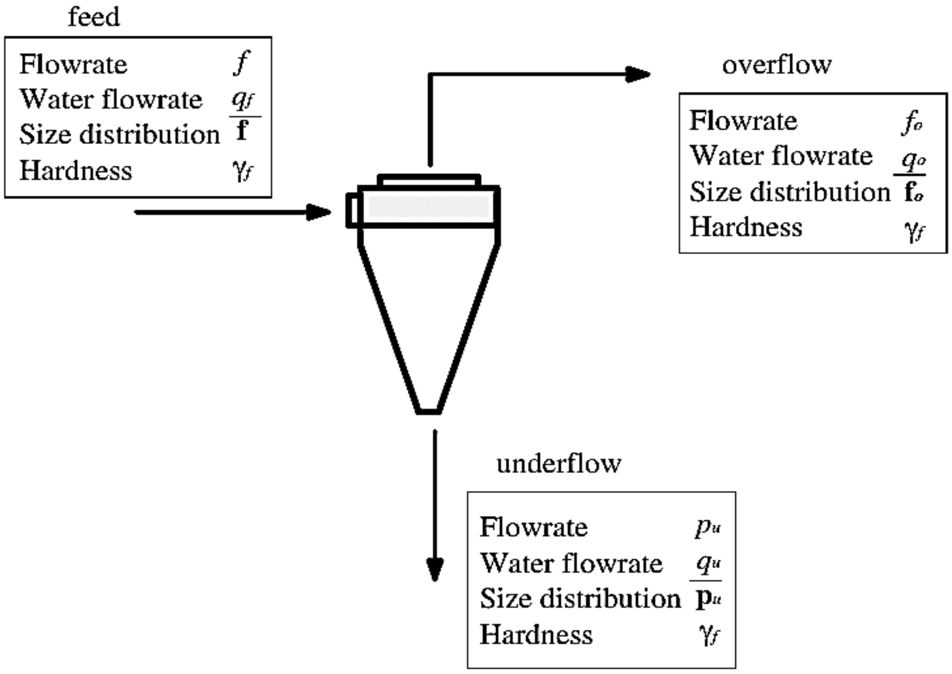
- flocculent consumption,
- pump power,
- discharges to tailings.

All these factors depend on the underflow density set point. Optimum conditions are usually ascertained by trial and error method by taking signals from the underflow density, pump discharge pressures and pump power drafts and estimating the corresponding cost functions.

Control of other allied operations:

Hydro-cyclone:

During steady operation the products from a hydrocyclone has a definite cut point. However due to variations in the feed slurry characteristics and changes in the hydrocyclone geometry, especially the diameter of the apex due to abrasion, the cut point changes during operation. It is necessary to hold the performance at the desired d_{50C} value for downstream operations.



(A hydrocyclone and its parameters)

The control strategy could be to monitor the deviation of the cut point. The alteration in cut point was obviously due to change in feed characteristics and additionally to changes in cyclone geometry due to abrasion. Study suggests that for a constant pressure differential, the relative effect on d_{50C} was:

$$D_U > \varphi_i > Q > H > T$$

where

Du = Diameter of apex in cm

φ_i = Volumetric fraction of solids in the feed slurry,

Q = Rate of flow in m^3 /min

H = Height of the cyclone in cm,

T = Temperature in ° C.

The logic of the control program adopted was to calculate the d_{50C} value during a steady state condition using a mathematical model. When the cut-point was altered due to any change in the variables the computer sequentially searched for the offending variable and restored it to the original value. The restoration was done by iteration using perturbance technique. The advantage of the technique was to predict changes using the previous reading as the initial value.

An important factor in designing control loops is the instrumental and programmable time delays. In the case of hydrocyclone automation, the sources of time delays is given below the Table.

Each instrument has to have a separate time delay factor which could be up to 3 seconds Programmable time delays introduced during iteration could be greater than instrumental time Delays

Source of time delays in a hydrocyclone circuit.

Equipment	Time delay source
Motor pump set	Frequency controller, Inertia in motor load.
Vortex finder positioner	V/I and I/P conversions, Pressure transmission, Mechanical movements, Servo- Mechanism operations
Spigot diameter	V/I and I/P conversions.
Density gauges and Flow meters	Electronic, Adjustable response time
Computer	Conversions

MODULE-IV

Instrumentation for measurement:

Instrumentation refers to the group of devices that work together to control one or more variables.

Objective:

- Measurement and control
- Prevent equipment overload
- Direct equipment problems like stoppage, partly failure etc.
- Can calculate complex mathematical calculations to increase efficiency

Process variables:

It is a condition of the process that can change.

Basic variables are pressure, flow, level, temperature, density, pH, mass, conductivity etc.

Measurement:

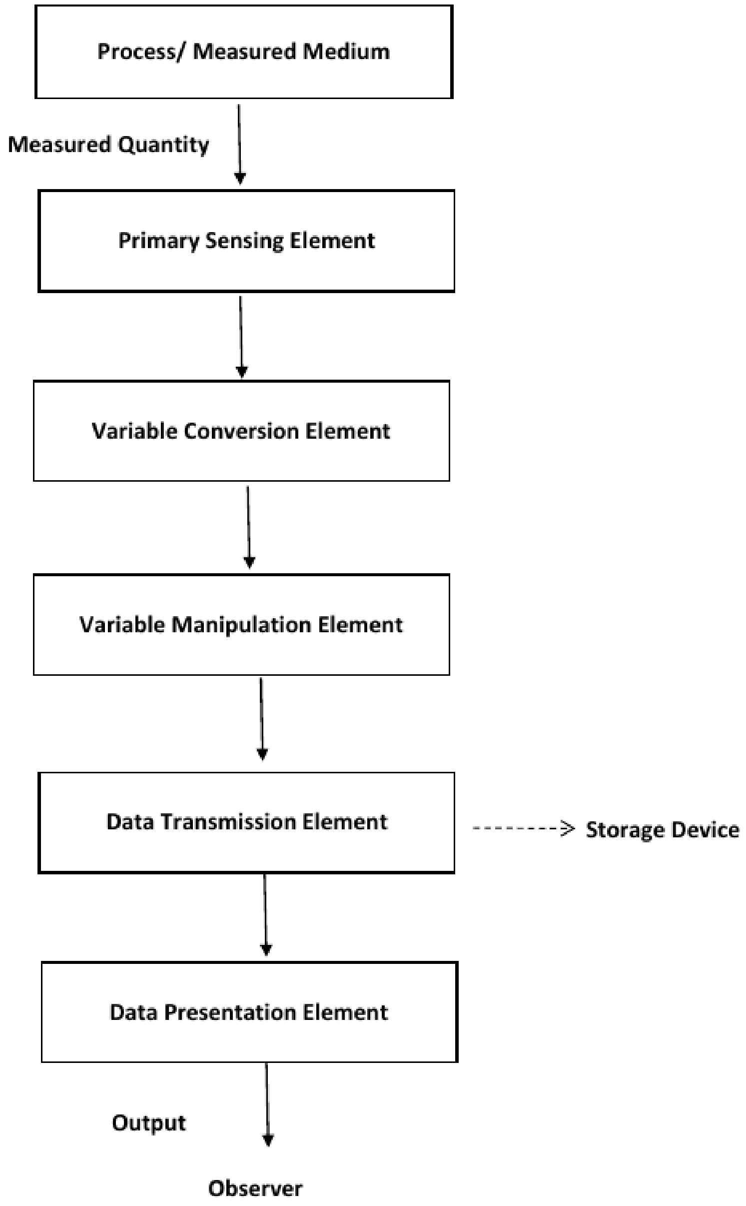
It is the comparison between a quantity whose magnitude is unknown with a similar quantity whose magnitude is known(standard) to get a result. The standard is used for accuracy.

Basics of measurement:

a. Range: Lower to higher limit of measurement
b. Span: Mathematical difference between upper and lower range
c. Accuracy: Degree of closeness of measured value of the actual value
d. Repeatability: The degree to which repeated measurements under the exact same condition produces same results.

Measurement Elements:

The measurement process can be described as follows:



The usual instruments covering the regulatory levels in mineral processing plants are shown below:

Instruments and their uses in mineral processing plants

Instrument	Property measured and use
Weightometer	Measures mass flow rate of material. Usually a small length of conveyor belt rests on load cells
Level indicator	Measures level by, ultrasonic, pressure differential or simply by a float-ball
Flow meters	Measures mass rate of flow generally by non-invasive methods. like Magnetic flow meters, Ultrasonic flow meters.(Doppler effect) The invasive types include orifice flow meters.
Density gauges	Measures fluid and pulp densities either on stream with Gamma ray density gauges, or by taking samples and using Marcy density gauge.
Pressure gauges / Thermo-couples	Measures pressure or pressure differentials pneumatic,/hydraulic systems and temperatures
Particle size analyzer	Measures particle size passing a particular sieve size, e.g., 75 microns on stream (OSA) by generating ultrasonic signals
pH indicator	For measuring acidity and alkalinity of solutions
D/A-A/D converter	For converting digital to analog signals and analog to digital signals
Attenuators	Converting amplitude of input/output signals.

On-line particle size distribution:

Continuous measurement of particle size in slurries has been available since 1971, the PSM system produced then by Armco Autometrics, subsequently by Svedala and now by Thermo Gamma Metrics (ThermoFisher Scientific) having been installed in a number of mineral processing plants.

The PSM system consists of three sections:

a. the air eliminator
b. the sensor section
c. the electronics section

The air eliminator draws a sample from the process stream and removes entrained air bubbles. The de-aerated pulp then passes between the sensors. Measurement depends on the varying absorption of ultrasonic waves in suspensions of different particle sizes. Since solids concentration also affects the absorption of ultrasonic radiation, two pairs of transmitters and receivers, operating at different frequencies, are employed to measure particle size and solids concentration of the pulp, the processing of this information being performed by the electronics.

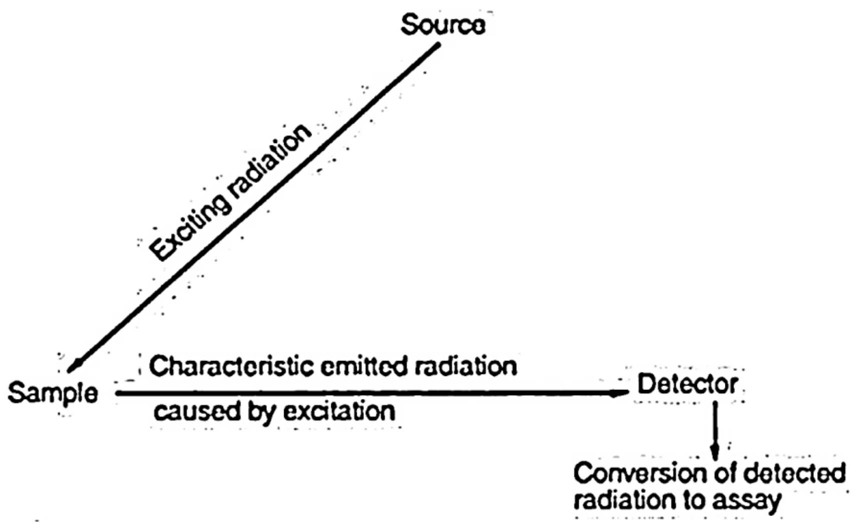
An example is PSM, ThermoFisher Scientific PSM-400MPX, which handles slurries up to 60% solids w/w with output of five size fractions simultaneously.

Other measurement principles are now available in commercial form for slurries. The Outokumpu PSI 200 system measures the size of individual particles in a slurry stream directly using a reciprocating caliper sensor which converts position (and thus size) into an electrical signal. Outokumpu has also developed an on-line version of the laser diffraction principle the PSI 500.

Metallurgical Grade analysis

The benefits of continuous analysis of process streams in mineral processing plants led to the development in the early 1960s of devices for X-ray fluorescence (XRF) analysis of flowing slurry streams. On-line analysis enables a change of quality to be detected and corrected rapidly and continuously, obviating the delays involved in off-line laboratory testing. This method also frees skilled staff for more productive work than testing of routine samples.

The principle of on-line analysis is shown below:



(Online chemical analysis)

Basically, it consists of three main parts:

- A source of radiation
- A detector

The radiation is absorbed by the sample and causes it to give off fluorescent response radiation characteristic of each element. This enters a detector which generates a quantitative output signal as a result of measuring the characteristic radiation of one element from the sample. The detector output signal is generally used to obtain an assay value which can be used for process control.

Two practical methods of on-line X-ray fluorescence analysis are:

- Centralised X-ray (on-stream) system
- In-stream probe systems

Centralised on-stream analysis employs a single high-energy excitation source for analysis of several slurry samples delivered to a central location where the complete equipment is installed. In-stream analysis employs sensors installed in, or near, the slurry stream, and sample excitation is carried out with convenient low-energy sources, usually radioactive isotopes. This overcomes the problem of transporting representative samples of slurry to the analyser. The excitation sources are packaged with a detector in a compact device called a probe. Centralised analysis is usually installed in large plants, requiting continuous monitoring of many different pulp streams, whereas smaller plants with fewer streams may incorporate probes on the basis of lower capital investment.

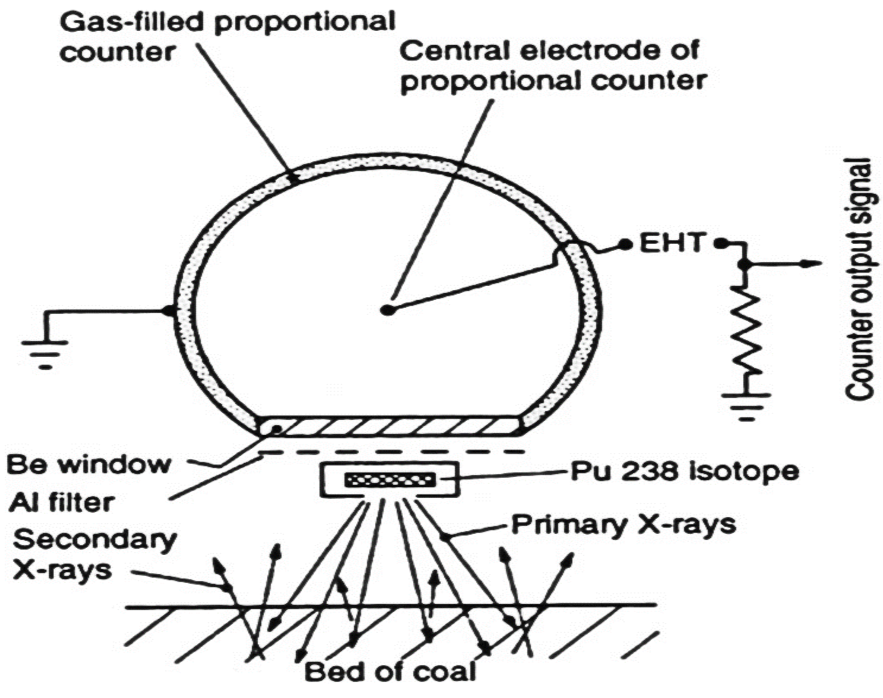
One of the major problems in on-stream X-ray analysis is ensuring that the samples presented to the radiation are representative of the bulk, and that the response radiation is obtained from a representative fraction of this sample. The exciting radiation interacts with the slurry by first passing through a thin plastic film window and then penetrating the sample which is in contact with this window. Response radiation takes the opposite path back to the detector. Most of the radiation is absorbed in a few mm depth of the sample, so that the layer of slurry in immediate contact with the window has the greatest influence on the assays produced. Accuracy and reliability depend on this very thin layer being representative of the bulk material. Segregation in the slurry can take place at the window due to flow pattens resulting from the presence of the window surface. This can be eliminated by the use of high turbulence flow cells in the centralised X-ray analyser. Operating costs and design complexities of sampling and pumping can be largely avoided with the probe-measuring devices positioned near the bulk stream to be assayed, noting the requirement for turbulent flow of representative slurry sample at the measurement interface of the probe.

Online coal analysis:

On-stream monitoring of the ash content of coals is being increasingly used in coal preparation plants to automatically control the constituents which make up a constant ash blend. The operating principle of the monitor is based on the concept that when a material is subjected to irradiation by X-rays, a portion of this radiation is absorbed, with the remainder being reflected. The radiation absorbed by elements of low atomic number (carbon and hydrogen) is lower than that absorbed by elements of high atomic number (silicon, aluminium, iron), which form the ash in coal, so the variation of absorption coefficient with atomic number can be directly applied to the ash determination.

Construction and operation:

A representative sample of coal is collected and crushed, and fed as a continuous stream into the presentation unit of the monitor, where it is compressed into a compact uniform bed of coal, with a smooth surface and uniform density. The surface is irradiated with X-rays from a plutonium 238 isotope and the radiation is absorbed or back- scattered in proportion to the elemental composition of the sample, the back-scattered radiation being measured by a proportional counter. At the low-energy level of the plutonium 238 isotope(15-17keV), the iron is excited to produce fluorescent X-rays that can be filtered, counted, and compensated. The proportional counter simultaneously detects the back-scattered and fluorescent X-rays after they have passed through an aluminium filter. This absorbs the fluorescent X-rays preferentially, its thickness preselected to suit the iron content and its variation. The proportional counter converts the radiation to electrical pulses that are then amplified and counted in the electronic unit. The count-rate of these pulses is converted to a voltage which is displayed and is also available for process control.



Slurry flow rate measurement:

Flow is defined as the rate (volume or area per unit time) at which a substance travels through a given cross section and is characterized at specific temperatures and pressures. The instruments used to measure flow are termed flow meters.

The main components of a flow meter include the sensor, signal processor and transmitter. Flow sensors use acoustic waves and electromagnetic fields to measure the flow through a given area via physical quantities, such as acceleration, frequency, pressure and volume. As a result, many flow meters are named with respect to the physical property that helps to measure the flow. Most importantly, accurate flow measurements ensure the safety of the process and for those involved in its success.

There are different types of flow meters:

- Differential Pressure type:

These sensors work according to Bernoulli's principle which states that the pressure drop across the meter is proportional to the square of the flow rate.

Example: Orifice meter, Venturi Meter, Flow Nozzle, Pitot Tubes etc.

- Direct force type:

These flow meters are governed by balancing forces within the system.

Example: rotameter, Turbine Meter etc.

- Frequency type:

These flow meters use frequency and electronic signals to calculate the flow rate.

Example: Vortex Shedding Flow Meter

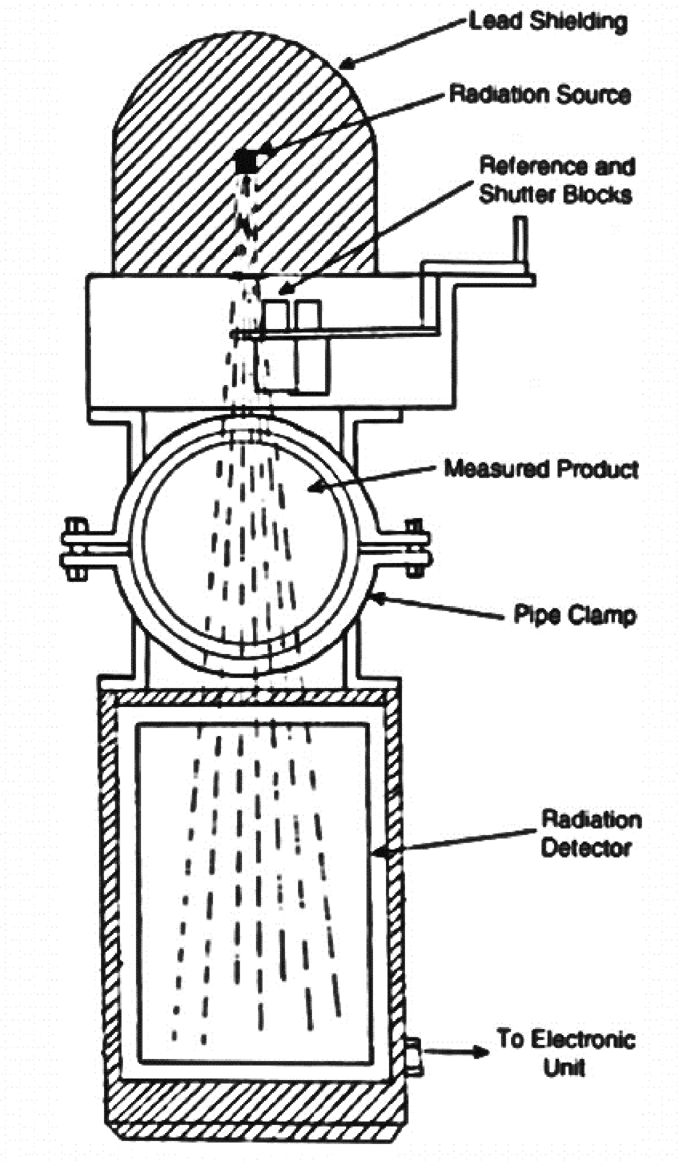
- Ultrasonic Flow Meters:

The basis for these meters is monitoring ultrasonic waves in fluid passing through a pre-configured acoustic field. These meters are based on the technique of sound waves that change.

Example: Transit Time Flow Meters

Pulp density measurement:

The density of the slurry is measured automatically and continuously in the nucleonic density gauge by using a radioactive source. The gamma rays produced by this source pass through the pipe walls and the slurry at an intensity that is inversely proportional to the pulp density. The rays are detected by a high-efficiency ionisation chamber and the electrical signal output is recorded directly as pulp density.



(Nucleonic density gauge)

Fully digital gauges using scintillation detectors are also now in common use. The instrument must be calibrated initially on-stream using conventional laboratory methods of density analysis from samples with- drawn from the line.

Level Sensor: (pulp level, froth level etc.)

Level sensors allow for the level control of fluid in a vessel. Examples of where these sensors are installed include flotation cells, thickeners, slurry tanks, mixing tanks, etc. Level sensors provide operators with three important data for control:

- the amount of materials available for processing,
- the amount of product in storage,
- the operating condition.

Installing the correct level sensor ensures the safety of the operator and the surrounding environment by preventing materials in vessels from overflowing or running dry. There are several different types of level monitors, including:

- Visual
- Float
- Valve Controlled
- Electronic
- Radiation

These different types of sensors can also be grouped into categories of process contact and non-process contact. As the name suggests, process contact sensors are within the tank, in physical contact with the material. Non-process contact sensors transmit various types of signals to reflect off of the material and thus measure the level. Non-process contact sensors can be used for the purpose of process control. Most of the industries now a days uses radiation type level sensor to get the signal with accuracy and required form.

Radiation-based Level Sensors:

Radiation-based level sensors are based on the principle of a material's ability to absorb or reflect radiation. The common types of radiation used in continuous level gages are ultrasonic, radar / microwave and nuclear.

- **Ultrasonic (Sonic) Level Sensors:**

Ultrasonic level sensor transmitters emit high frequency ultrasonic acoustic waves which are reflected back by the medium to the receivers. By measuring the time it takes for the reflected echo to be received, the sensor can calculate the actual distance between the receiver and the fluid level. These sensors can be accurate from a distance of 5mm to 30m.

- **Microwave / Radar Level Sensors:**

Microwave / radar level sensors are similar to ultrasonic level sensors in that they require a transmitter and receiver. In addition to these materials, radar sensors also need an antenna and operator interface to use electromagnetic waves to calculate level distance.

- **Nuclear Level Sensors:**

Nuclear level sensors rely on gamma rays for detection. Although these gamma rays can penetrate even the most solid of mediums, the intensity of the rays will reduce in passage. If the gamma ray emitter and the detector are placed on the top and bottom of a vessel, the thickness of the medium (level) can be calculated by the change in intensity.

Ball mill load measurement:

The measurement of ball mill load has an important role to ensure safety, improve efficiency and reduce energy consumption. Because the ball mill load was influenced by many factors, its measurement is difficult which is still a technological difficulty.

So far, the main methods to measure the ball mill load are direct and indirect methods.

- **Direct Method:**

The direct method use pole to measure the height of ore pulp liquid level to get the load. As the pole damage and installation is a common problem, this method cannot be that much effective.

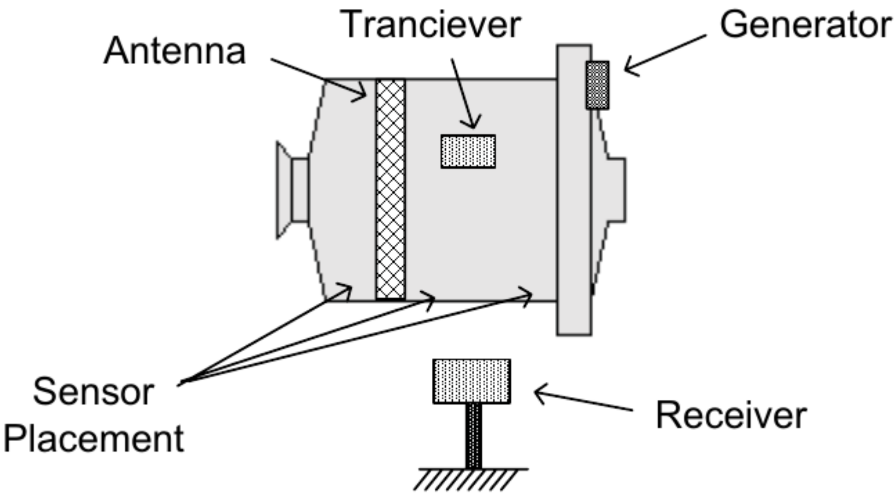
- **Indirect Method:**

The indirect method includes audio frequency method, vibration signal method, active power method, air pressure method etc.

The recent development includes a CCM (Continuous Charge Measurement) system, which is dedicated to continuous measurement of the charge volume and the angle of repose provided that the mill has a rubber or rubber-metal mill lining or that a sensor-equipped rubber lifter bar can be installed in a steel-lined mill. The equipment consists of three main parts;

- the sensor,
- the telemetry system
- the computer for data analysis and presentation.

The most exposed component is the sensor, since the mechanical environment is very stressful due to the number of deflections of the sensor spring is far above the normal fatigue limit. Furthermore, the sensor is exposed to moisture with temperatures between 30-60^0 C and also to high stress during parts of every revolution. The mill has a number of lifters on the inside of the mill shell. One of these lifters is equipped with a leaf spring whose deflection is measured by the strain gauge. As the mill rotates and the lifter with the sensor dips into the charge, the force acting on the lifter increases, which in turn, causes a deflection. The strain gauge mounted on the leaf spring converts this deflection to an electric signal. The signal is then amplified, filtered and transformed to a pulse with a modulated HF-signal in the transceiver and by the antenna wired around the mill transmitted to the receiver placed close to the mill. A pendulum driven generator placed on the mill end produces the power to the transceiver. The receiver has also a trigger pulse that is activated once every revolution. This is for the system to know when a new revolution occurs. Finally, the signal is transmitted by cable to the measurement computer where the calculation, analysis and presentation of the signal is done.



(A Continuous Charge Measurement System)

Reference:

1. Wills, B.A. and Napier-Munn T., Mineral Processing Technology, Elsevier Science & Technology Books
2. Gupta A. and Yan D.S., Mineral Processing Design & Operation, Elsevier 2006
3. Sbárbaro.D. and Villar R.D., Advanced Control and Supervision of Mineral Processing Plants, Springer publications
4. Chemical Process Dynamics and Controls, University of Michigan
5. Seborg D.E., Edgar T.F., Mellichamp D.A. and Doyle III F.J., Process dynamics and control, Wiley
6. Jana A.K. and Sarkar.D, Process Control and Instrumentation - Video course, NPTEL