CHAPTER 1

1. INTRODUCTION

1.1 General overview

Automatic process control is an integral part of the process industries like chemical processing, pharmaceutical, biochemical, and power generating plants. Automatic process control requires in-depth knowledge of control engineering and chemical engineering disciplines, and implemented in the process industries to accomplish optimum production level with quality, follow the environment and safety regulations, economy, which is not possible to achieve by manual control. Several fluctuating parameters like temperature, level, concentration, pressure, pH may exist in the process industries. A proper control algorithm is needed for control of these parameters and to achieve optimum plant operation. In the automatic process control, it is possible to achieve reasonable control by manipulating a small number of variables. The applications of the process control may vary from controlling a single variable like temperature and level to a complete chemical processing plant with several thousand control loops.

Various advanced control techniques such as Model Predictive Control (MPC), adaptive control, gain scheduling, inferential control, and fuzzy logic-based control, have been developed and used in the process industries to achieve optimum plant operation. Despite the development of advanced control, more than 95% of the process industries are still using PI/PID controller [1]. The control loops used in the chemical or biochemical industries may not be well-tuned because they still use conventional controller tuning techniques like Ziegler-Nichols [2] and Cohen-Coon [3] due to their great simplicity. These two tuning techniques do not provide satisfactory results in many cases and sometimes show a significant deviation from the control objectives provided by control engineers. Different researchers have shown that the PID controller tunned with better tuning techniques such as Internal Model Control (IMC) and Direct Synthesis (DS) may provide simple and cost-effective solutions to most of the problems related to process industries.

1.2 Historical Background

The control techniques have been developed and used in the early 17^{th} century. Christiaan Huygens had done significant work in the field of control techniques. This control approach was applied to maintain the gap between millstones in windmills, and finally, it controlled the variable speed of grain feed [4, 5]. In the early age of 18^{th} century, James Watt [6] developed an automatic control technique based on self-designed, "conical pendulum" governor, a set of revolving steel balls attached to a vertical spindle by link arms, and applied for automatic speed control of a steam engine. The speed control of governor was varied by a varying load, and this was known as proportional action. The error between the desired speed and the actual speed was increased by increasing load. The proportional controller became unstable and went into significant overshoot if the controller gain increases to a high value [6]. James Clerk Maxwell [7] gave the first theoretical description of a governor in 1868 in his famous paper on governors. The mathematician discussed the problem of control stability and analyzed it mathematically set of techniques to get a reasonable solution [6,7].

Further, an American scientist Willard Gibbs redefined the governor speed in 1872 and analyzed Watt's conical pendulum governor theoretically. The pendulum was known as derivative control and obtained a damped oscillation by detecting the torpedo dive/climb angle and thereby the rate of depth [8]. Elmer Sperry in 1911, developed a control mechanism similar to a PID-type controller for ship steering, which was more intuitive rather than mathematical-based. A proper control algorithm in the form of a PID controller was established by a Russian American engineer, namely Minorsky (1922), for steering ships and used the system differential equations for the study of its stability. He was a control engineer in the US Navy, and he designed an automatic ship steering based on observation of helmsmen. He observed that the helmsmen steered the ship based on current error, past error as well as the current rate of change, and then he provided a mathematical rule for ship steering mainly for attaining stability of the ship [9]. He analyzed and showed that the proportional controller was able to eliminate small error and failed to control long term error or steady error, and hence, an integral term was added. The derivative term was included for stability and to control future errors. He analyzed and provided the role of proportional, integral and derivative action in the PID controller.

The negative feedback control scheme became feasible to use only after the development of a wideband high-gain amplifier. A wide-bandgap pneumatic controller using flapper and nozzle element was invented by Clesson E Mason of the Foxboro Company in 1930 for negative feedback system. The use of wideband pneumatic controllers increased rapidly after 1932 for control applications. The controller output was generated by using the pneumatic controller, and finally, the control action implemented on the process using a diaphragm-operated control valve. Later on, an electronic PID controller was developed in the 1950s. Rational combination of instruments worked together according to certain principle known as control theory and performed the desired task in an automatic manner, the system is known as an automatic control system. If machines complete tasks with no human intervention, the system is known as fully automatic, and if the task is partially completed by machines and operators, then it is called semi-automatic. In the control system, four essential components namely process, measuring elements, controller, and final control element were identified by the control engineers and its role and importance are described in the subsequent sections.

1.3 Process

The process is the combination of the processing operations (physical, chemical, mechanical, or thermal) and processing equipment (reactor, heat exchanger, distillation columns, evaporator, extractor, etc.), which convert the feed to the product as shown in Fig. 1.1. There are three different types of processes found in industries, namely continuous, batch, and semi-batch.

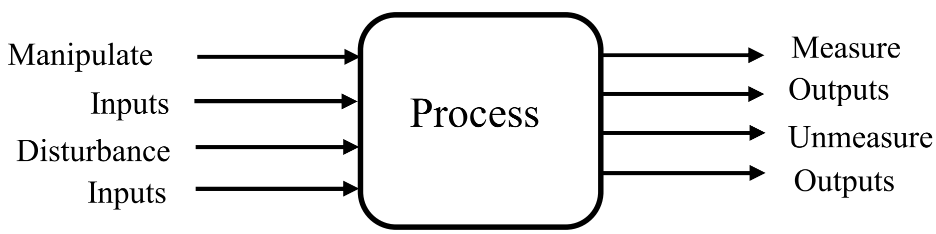

Fig. 1.1 General process system

After the development of a negative feedback system and its great usefulness in automation, the control system's popularity for achieving the optimum production level with the quality of the product and safe plant operation. The importance of the control system increased rapidly in the 19th century due to increasing complexity of the industrial process. A proper control strategy also assured an improved quality of the products, low production cost, higher efficiency and safety during plant operation. After 1930, tremendous progress had been made in the control techniques, and hence, the modern plants use computer-based process control systems to maintain the desired product quality, economical operation, while satisfying environmental requirements. Due to the development of control theory, it is possible to operate large-scale integrated process industries in a fully automatic manner like petroleum refineries having complex control loop structures due to the presence of thousands of loops with process variables such as temperature, compositions, level, and pressure.

The control systems mainly do three essential tasks, as given below.

a. Measure the process variable by measuring elements
b. Making of decision for taking necessary action to achieve the desired state based on information on the current state of the process.
c. Implementing these decisions to process

For simple processes, an operator can perform the tasks mentioned above with the help of suitable instruments, and this is known as manual control. For complicated processes, it is not possible to complete the above task manually and so automatic systems are an essential component of any complicated process.

1.4 Mathematical Modeling

The dynamic behavior of the control system should be known for the implementation of a suitable control strategy. Mathematical modeling is an excellent and cost-effective tool for analyzing the dynamic behavior of the system under the continuous change in various process parameters. The mathematical modeling is a mathematical equivalent of a physical system and represented by different types of mathematical equations. Different modeling approaches are used to develop a mathematical model of a control system. For example, fundamental mathematical models are developed by conservation laws or by balance equations of mass, momentum, and energy. The selection of modeling approaches mainly depended upon the nature of processes. The mathematical model should be simple and reasonably accurate. It is difficult to obtain exact mathematical models of any system because sometimes the theory of the phenomenon is not entirely known; sometimes the experimental facts are not available; sometimes there is no need to include all details-often we look for the trends. The mathematical model of a process can be categorized in the following classes based on their characteristics behavior as listed in Table 1.1.

Table 1.1 Model classification [10]

Group of models	Classification	Criterion of classification
I	Mechanistic	Based on Mechanism/underlying phenomena
	Empirical	Based on input-output, trials or experiments
II	Stochastics	Contains model elements that are probabilistic nature
	Deterministic	Based on a cause-effect analysis
III	Lumped parameters	Dependent variables not function of special position
	Distributed parameter	Dependent variables are fuunction of special position
IV	Linear	Super position principle applies
	Nonlinear	Superposition principle does not apply (occurrence of the product of dependent variables and or its derivatives)
V	Continuous	Dependent variables defined over continous space time
	Discrete	Only defined for discrete values of time/ or space
	Hybrid	Containing continuous and discrete behavior

1.5 Control Techniques

Different control techniques, as shown in Fig. 1.2 have been developed by various researchers based on the requirements of the process. Fig. 1.2 shows the hierarchy of the various control approaches used in chemical, biochemical, and pharmaceutical industries at a different level of the control loop.

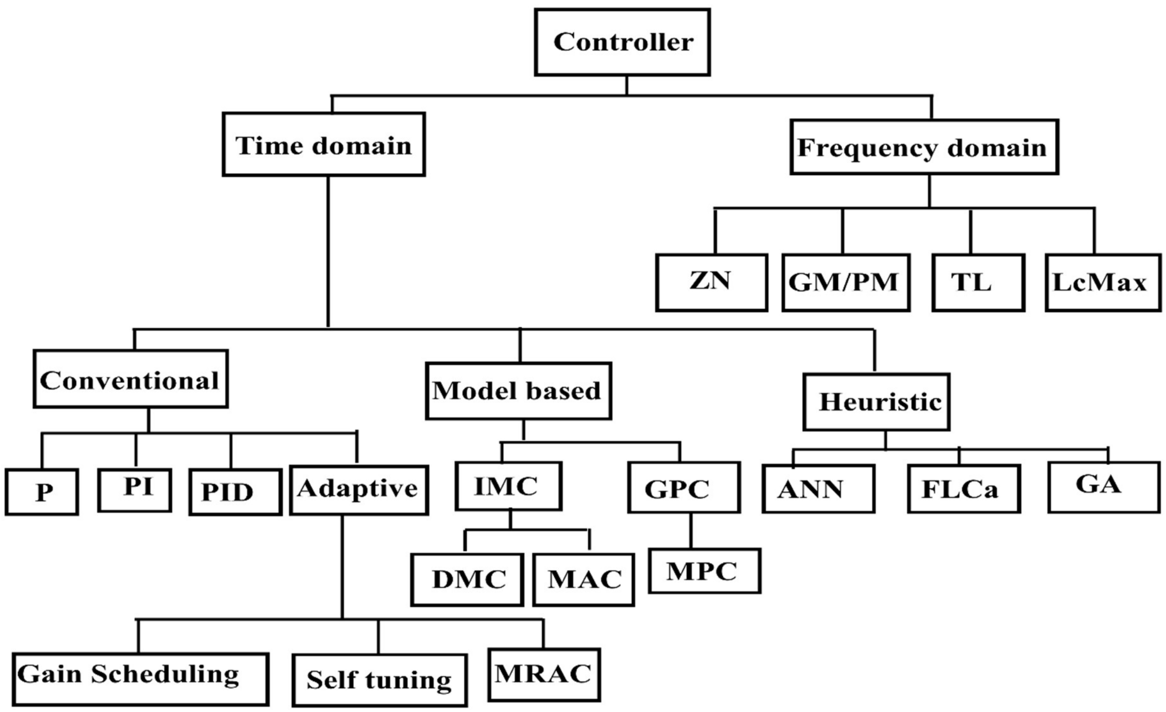

Fig. 1.2 Hierarchy of the various control approaches used in process industries [11].

Various conventional and advanced control techniques, including PID tuning techniques, have been shown in Fig. 1.2. However, despite the development of advanced control techniques, most of the control loops of the process industries still used PI/PID controller, at least in the bottom layer control-loop, due to its simple structure and easy implementation [1]. Different types of conventional and model-based PID design techniques use in the process industries are as follows:

- Tuning based on Identification
  - Ziegler-Nichols closed-loop method
  - Cohen-Coon method
  - Relay feedback methods
  - Online Optimization-based methods
- Model-based tuning
  - Internal Model Control (IMC) method
  - Direct synthesis method
  - Delay compensation techniques (Smith predictor, analytical predictor)
  - Optimization-based methods

Conventional PID tuning rules Ziegler-Nichols [2] and Cohen-Coon [3] are widely used in chemical or biochemical process industries to the processes which can be easily approximated to first order plus time delay (FOPDT) model. These two design methods are based on the open-loop step test to calculate three process parameters, namely process gain (k), time constant (τ), and time delay (θ) for finding the controller setting. In the implementation of the above methods, there are mainly two types of difficulty arises. First, an open-loop experiment has to be performed with a step-change in any input to obtain the process model parameters. The second problem arises due to error approximation in obtaining the process parameters ($k, \tau\ and\ \theta$). Further, there is always possiblity of the control variable moving away from its set-point value and which leads to giving off-specification product qualities. To overcome the problems associated with the open-loop controller design method, Z-N developed a closed-loop PID tuning rule. In the processes tunned with a closed-loop approach, it was easy to obtain the specified product qualities and minimize the effects of external disturbances. Ziegler-Nichols' closed-loop PID tuning rule requires only the ultimate controller gain (Ku) and the period of oscillations (Pu) to obtain the controller setting. The parameters Ku and Pu can be calculated directly by conducting the closed-loop experiments. This approach is widely used in process industries. However, it has several disadvantages. In the closed-loop Z-N approach, one has to push the process on the verge of instability to obtain Ku and Pu. Reaching the ultimate value of the process response or obtaining ultimate gain is time-consuming, but the system may become unstable at least for a short period if we make a significant adjustment to get Ku. These tuning approaches do not show satisfactory closed-loop performance for a process having a higher time delay, integrating and unstable.

The model-based techniques for the designing of a PID controller were invented to overcome these issues. The model-based controller design is advantageous if a reasonably detailed dynamic of the process is available. A wide variety of model-based design rules for PID controller are available in the literature out of which Direct Synthesis (DS) and Internal Model Control (IMC) are widely studied by the researchers. These two methods are similar in the designing procedure of PI/PID controller and applied to a wide variety of first and second-order plus time delay process models for integrating stable and unstable systems.

In the direct synthesis (DS) approach, a desired closed-loop transfer function model for set-point change is assumed in the designing of PI/PID or PID in series with lead-lag filter. The controller is designed so that the closed-loop set-point response matched to the desired closed-loop transfer function model. This tuning approach was initially developed for setpoint tracking, but later, it was also used for disturbance rejection. In process industries, the disturbance in the input is more critical than the set-point change, and it is more difficult to control the process variable at the desired level [12]. In the DS method, the performance requirement of the closed-loop is incorporated in the desired closed-loop transfer function. The choice of the desired closed-loop response means the selection of the closed-loop poles. The DS approach is considered as a specific type of pole placement method. The DS method has the main drawback that it shows improved closed-loop performance for the set-point change but provides a sluggish response for input (load) disturbance. For chemical processes, the load change is more critical than the set-point change[13].

A more extensive model-based design technique, Internal Model Control (IMC), was developed byMorari and associates [14, 15]. A model-based design approach similar to the DS method was applied for designing of IMC controller and which leads to obtaining analytical expressions for controller settings. These analytical expressions can be converted into PID form and provide PID controller settings. The IMC design technique is a two-step design procedure that aims to give a suitable tradeoff between performance and robustness. In Step 1 a stable and causal controller is obtained i.e., optimal with respect to either the integral of squared error (ISE) or integral of absolute error (IAE) criteria for step changes to the control system. The second step augments the controller from Step 1 with a filter to ensure that the IMC controller is proper and realizable. For many simple processes of interest, the IMC controller simplified leads to a PID-type controller [16]. The great advantage of IMC is that it has a single tuning parameter. A trade-off between performance and robustness may obtain by selecting an optimum value of the tuning parameter. The IMC can be used more accurately in case of model uncertainty and process model mismatch. This technique has also been used to developed controller for many forms of the process such as single-input, single-output (SISO) and multi-input, multi-output (MIMO), continuous, and discrete-time, unstable open-loop process and combined feedback-feedforward IMC design.

In the current scenario, the DS and IMC techniques based PI/PID controller or PID controller with a lead-lag compensator in series are widely used to control different types of processes. These tuning techniques are extensively used to control a first and second-order time delay of integrating, stable and unstable process models in chemical and biochemical processes. Improved closed-loop performance may obtain in both the cases of set-point tracking and load change by selecting a proper filter in the designing of the IMC-PID controller [17-19].