Chapter 3

INTRODUCTION TO INTELLIGENT CONTROL

3.1 Introduction

In recent years, control systems have assumed increasingly important role in the development and advancement of modern civilization and technologies. Practically every aspect of our day-to-day life is affected by some type of control system. This chapter presents an overview of control engineering developments. The conventional control technique, i.e. the PID control and its related developments and the limitations are reviewed. The requirements of the Intelligent Control (IC) methods are introduced to cater to the limitations of the PID control technique. Various components of ICs such as Computational Intelligence (CI), Evolutionary Computing (EC) and Soft Computing (SC) in control engineering applications are also presented.

3.2 Brief history of control engineering developments

Automatic addition to control has played a vital role in the advancement of engineering and science. In addition to its extreme importance in space-vehicle systems, missile-guidance systems, robotic systems and the like, automatic control has become an important and integral part of current day modern manufacturing and industrial processes. Process control engineers are concerned with maintaining good quality process output variables. This requirement has affected the specifications of the controller performance for achieving the desired goal. As control engineering technology progressed more refined and complex specifications were developed in order to cater to the needs of the modern industry. The advancement of the digital systems and computing technology has further revolutionized the automatic control. Computer controlled digital systems are especially useful for control of complex systems. Automatic control as a subject has also now acquired importance in several other branches of engineering [Smith & Corripio, 1985].
The first important application of control engineering was related to speed control of steam engines using a centrifugal governor by James Watt in the second half of eighteenth century; the dynamics of control system was studied a century later. Other significant works in the early stages of development of control theory were due to Minorsky, Hazen, Nyquist and many others. In 1922, Minorsky worked on automatic controllers for steering ships and showed how stability could be determined from the differential equations describing the system. Nyquist, in 1932 developed a relatively simple procedure for determining the stability of closed-loop system on the basis of open-loop response to steady state sinusoidal inputs. In 1934, Hazen, who introduced the term servomechanism for position control system, discussed the design of relay servomechanisms capable of closely following a changing input. During the decade of 1940, frequency response methods by Bode and in 1950 root-locus method due to Evans were developed. During the years from 1960 to 1980 optimal control, as well as adaptive and learning control system were evolved.

The dramatic development of inexpensive and powerful computer technology has radically changed the boundaries of control systems. Subsequent developments, on the analysis as well as the hardware took place in the last three decades. Computer controlled digital systems are especially useful for control of complex systems. It is now possible to employ, complicated and higher order digital controllers, to carry out the complex control task. On the analysis side, the complexity resulted in motivation to develop the modern control theory based on state space analysis. Modern control theory is centered on robust control, $H_\infty$ control, and associated topics. Implementation of nonlinear robust control schemes, model reference adaptive control, self tuning control, variable structure sliding mode control has now become simple task. In the process of understanding and emulating salient features of biological control functions, a new field called IC has emerged.

### 3.3 PID control

Traditionally industry has relied heavily on the classical PID control (also sometimes called three-term control because of its Proportional, Integral and Derivative action components)
which is incorporated today in most control systems [Lelic, 2000; Li, Ang & Chong, 2006]. The ubiquitous three-term controller is generally used to control almost all kinds of devices, industrial processes and manufacturing plants. PID controller remains an important control tool due to its past record of success, wide availability and simplicity in design and use. These reasons enforce one another, thereby ensuring that the more general framework of digital control with higher order controllers has not really been able to displace PID control. For example, it has been reported that more than 90% of control loops in Japanese industry are of PID type [Yamamoto & Hasimoto, 1991]. This is also believed to be true elsewhere [Swallow, 1991]. PID controllers continually attract attention, from both the academic as well as the industrial researchers, with many new recent studies being published [Luo, 1998; Grimble, 2001; Liu, et al., 2001; Silva, et al., 2002; Tokuda & Yamamoto, 2002; Zheng, 2002].

PID controller controls a process by working on the error, integral of the error and rate of change of the error. Error is computed as, \( e(t) = r(t) - y(t) \), where \( r(t) \) is the instantaneous value of the set point and \( y(t) \) is the instantaneous value of the process variable. Figure 3.1 shows the components of a typical closed loop feedback control system and Figure 3.2 shows a PID controller loop. Eq. [3.1] defines the PID control action in time domain. The three constants, \( K_P, K_I \) and \( K_D \) are normally called the PID controller gains. Parameter \( \tau \) is defined as the integral time constant. \( u(t) \) is defined as the PID controller output [Franklin, Powell & Naeini, 1986; Ogata, 1990].

\[
u(t) = K_P e(t) + K_I \int_0^t e(t) dt + K_D \frac{de(t)}{dt} \tag{3.1}
\]

![Figure 3.1: Components of a closed loop feedback control system.](image)
In the past, industry has had little option but to use classical control theory, based on macroscopic models of the plant, in designing appropriate conventional controllers. These methods depend on empirical knowledge of the dynamical behaviour of the controlled plant, derived from measurements of the control and manipulated variables of the plant. By choosing the values of three controller gains i.e. proportional term gain $K_P$, the integral term gain $K_I$ and the derivative term gain $K_D$ in the PID controller algorithm, the controller can provide control action designed for specific process requirements. The process of selecting appropriate values of these three constants is called the controller tuning. The main optimization parameters or performance criterion of a PID controller are normally in terms of its response to error, its overshoot, rise time and settling time or like. The main aim of the controller tuning is to generate a desired controller output $u(t)$, which helps the process to generate and track the desired output in best possible way. PID controller parameters are tuned such that the closed-loop control system would be stable and would meet the given objectives. These objectives are normally associated with stability robustness, set-point following and tracking performance at transient, regulation performance at steady-state, including load disturbance rejection, robustness against plant modelling uncertainty and noise attenuation and robustness against environmental uncertainty.

It may be noted that a high proportional gain results in a large change in the controller output for a given change in the error. If the proportional gain is too high, the system can become
unstable. Proportional kick is the term given to the observed effect of the proportional term in the usual parallel PID structure on rapid changes in the reference signal. As a result the actuator may be driven to saturation. One remedy for proportional kick is simply to restructure the controller, moving the proportional term into the feedback path. The contribution from the integral term sometimes called reset is proportional to both the magnitude of the error and the duration of the error. However, its high value could result in overshoot and the integral windup. It may again drive the actuator to saturation. Integral windup may be prevented by anti windup circuits or by redesigning the controller by making changes to its structure. The magnitude of the contribution of the derivative term sometimes called rate, to the overall control action is termed the derivative gain. However, the derivative term slows the rate of change of the controller output. Hence, derivative control is used to reduce the magnitude of the overshoot produced by the integral component and improve the combined controller-process stability. Derivative kick is similar to the proportional kick and the remedy is to reposition the derivative action. Various PID structures and configurations are proposed in the literature for catering to the above mentioned problems [Gerry, 1987; Kaya & Scheib, 1988; Gerry & Shinskey, 2004; Wilkie et al., 2005].

PID controller tuning is based on relatively simple approximants of the controlled plant dynamics and on design methods such as the classical ones by Nichols and Ziegler [Ziegler & Nichols (Z-N), 1942] or by Cohen and Coon [Cohen & Coon, 1953] or by more modern and improved techniques such those of Persson and Astrom and others [Graham & Lathrop, 1953; Astrom & Hagglund, 1984; Astrom, Hang & Persson, 1988; Hang et al., 1991; Astrom & Hagglund, 1995; Astrom, & Hagglund, 1999; Astrom, & Hagglund, 2005]. Many industrial process companies have in-house manuals that provide guidelines for tuning of the PID controller [Kinney, 1983] for particular plant. Some of these manuals based their procedure on the pro forma routines of the famous Z-N methods and its numerous extensions. In controller design, simple models are used to characterise the dynamics of a given plant. Based on this dynamic model, the PID parameters are then computed.
As mentioned above, conventional control systems design relies on the existence of an adequate macroscopic model of the physical plant to be controlled. The first stage in the analysis of such a system is therefore the development of an explicit mathematical model of the controlled plant that adequately reproduces the characteristics of the plant with fidelity. The model can be determined either from first physical laws or using some technique of system identification from operating data mined from the plant [Astrom & Eykhoff, 1971; Astrom & Wittenmark, 1971; Hagglund, 1983; Pessen, 1994; Liu & Daley, 2001; Pedret, 2002]. These days, this task is relatively made simple through the use of computer aided control systems design software with which the performance of the closed system can be rapidly evaluated and optimized [Glattfelder, Huguenin & Schaufelberger, 1980; Zhuang, 1992; Astrom, Panagopoulos & Hagglund, 1998]. The ultimate objective is clearly the development of a controller that satisfies specific performance specifications [Marsh, 1998; Tan, Yuan & Niu, 1999; Mann, Hu & Gosine, 2001; Tan, Liu, Chen & Marquez, 2006]. The design of a conventional controller, particularly in the case of multivariable plants, is a tedious and painstaking process that requires repeated cycles of analysis, synthesis and testing. The design normally converges to an acceptable solution and ultimately to commissioning. In order to use conventional design techniques, it is essential that the model of the plant be simplified and yet be sufficiently comprehensive so that it reproduces the essential dynamical features of the physical plant. It may be also noted that no physical system can be represented in its full physical intricacies and, therefore, idealizing assumptions are always made for the purpose of analysis and synthesis of systems.

Some researchers have investigated the controller design for specific cases. [Andreiev, 1981], proposed a self-tuning controller that continually optimizes PID constants. [Argelaguet, 1996], gave a new tuning method of PID controllers based on LQR optimization. [Zhuang & Atherton, 1991; Zhuang & Atherton, 1993], studied optimal tuning of PID controllers with integral performance criteria. The main purpose of this approach was to reduce the excessive overshoot of system compensated with Z-N controller. Self tuning regulators and controllers are also presented.
by [Astrom & Wittenmark, 1973; Astrom & Wittenmark, 1980; Zanker, 1980]. [Basilio & Matos, 2002], proposed a design of PI and PID controllers with transient performance specifications. The didactic method is based on the frequency domain approach.

Conventional PID controllers have been well developed for nearly a century [Bennett, 1993; Bennett, 2001]. Spurred by the rapid development of advanced micro-electronics and digital processors, these controllers have recently gone through technological revolutions from their version as pneumatic controllers implemented by analogue electronics to the current versions as microprocessors implemented by the digital circuits. Tuning of the PID gains is always challenge in the state of the art PID controller design. [Tan, Liu, Chen & Marquez, 2006], gives detailed comparative study of various tuning formulas. Tuning of the PID controller can be grouped according to their usage and nature, as follows.

a. **Analytical methods**: PID parameters are calculated from analytical or algebraic relations between a plant model and an objective (such as Internal Model Control (IMC) or lambda tuning). These lead to an easy-to-use formulas and can be suitable for use with online tuning, but the objective needs to be in an analytical form and the model need to be accurate.

b. **Heuristic methods**: These are evolved from practical experience in manual tuning (such as the Z-N tuning rules) and from Artificial Intelligence (AI). Some AI based methods are expert systems, fuzzy logic and neural networks. Again, these serve in the form of a formula or a rule base for online use, often with trade-off design objectives.

c. **Frequency response methods**: Frequency characteristics of the controlled process are used to tune the PID controller (such as loop-shaping). These are often offline and academic methods, where the main concern of design is stability robustness.

d. **Optimization methods**: These can be regarded as a special type of optimal control, where PID parameters are obtained *ad hoc* using an offline numerical optimization method for a single composite objective or using computerised heuristics or an evolutionary algorithm for multiple
design objectives. These are often time-domain methods and mostly applied off-line.

e. **Adaptive tuning methods:** These are for automated online tuning, using one or a combination of the previous methods based on real-time identification [Astrom, Borisson, Ljang & Wittenmark, 1977; Gawthrop, 1977; Gawthrop, 1980; Andreiev, 1981; Astrom, Anton & Arzen 1986; Astrom, & Hagglund, 1988; Hang & Sin, 1988].

The current trend in tackling PID tuning problem is to be able to use the standard PID structure to meet multiple design objectives over a reasonably range of operations and systems. Standardization or modularization around this structure is expected to help improve cost-effectiveness of PID control and its maintenance. This way, robustly optimal tuning methods are developed, as evident in PIDeasy [Feng, Tan, Zhu, Guan & Ang, 1981]. With the inclusion of system identification techniques, the entire PID design and tuning process is automated and modular building blocks can be made available for timely online application and adaptation. This feature is particularly suited to “system-on-board” or “system-on-chip” integration for future consumer electronics and Micro-Electronic-Mechanical-Sensors (MEMS).

### 3.4 Limitations of PID control

Modern manufacturing plants are required to meet increasing demands for more flexible production and improved quality while striving to meet stringent environmental constraints. The design of simple, practical and robust controllers for industry is usually based on low order holistic models of the physical plant as mentioned earlier. These approximants form the basis for the design of industrial controllers that satisfy relaxed performance criteria. PID controllers are the backbone of industrial control and these ubiquitous, simple and robust controllers have offered sterling service. However, these controllers can only perform at their best at the nominal operating point of the plant about which the approximant model holds [Ang, Chong & Li, 2005]. Although PID can be analytically designed and pre-tuned for precisely given lower-order linear systems, they have to be
manually operated for most practical systems that involve higher-order components, nonlinearities and uncertainties [Astrom & Hagglund, 2005].

To find easy ways of choosing suitable control gains in these controllers, Ziegler and Nichols [Z-N, 1942] and Cohen and Coon [Cohen & Coon, 1953] of the Taylor instrument company initiated the now well known heuristic rules for experimental design and tuning methods. When the operating point moves away from the nominal point, their performance is invariably degraded due to the inherent non-linearity, time variance and complex un-modelled dynamics of the physical plant. Because of the nonlinearities and uncertainties of a system conventional static control approach find limitations to achieve the designed specifications. A number of techniques have been proposed to anticipate this problem, the most common example of which is Gain-Scheduling (GS) and adaptive control. In GS the controller gains are updated at run time to cater to the dynamic needs of the process. The objective here is of extending the domain over which satisfactory controller performance is maintained [Zhao, Tomizuka & Isaka, 1993; Tan, Hang & Chai, 1997; Blanchett, Kember & Dubay, 2000; Li, Ang & Chong, 2006]. Fuzzy logic as a model to mimic the experienced operator is adapted to the design of auto-tuning PID. Besides the direct combination of the fuzzy logic and PID controllers, some non-conventional PID controllers employing fuzzy logic have also been developed [Chen, 1996; Chen & Pham, 2000; Ying et al., 1990].

For efficient controller tuning some new intelligent techniques are also reported. One of these methods called Genetic Algorithms (GA) work on the Darwinian principle of natural selection. They possess an intrinsic flexibility and freedom to search for a desirable solution according to the design specifications. Whether the specifications are non-linear, constraint or multi-model, GAs are entirely equal to the challenge. In addition, they have the distinct advantage of being able to solve the class of multi-objective problems to which controller design often belongs. GAs are being used to tune the PID controller by finding the best combination of controller gains within a defined search space [Bandyopadhyay, Chakraborty & Patranabis, 2001;
Adaptive controllers [Feuer & Morse, 1978; Egardt, 1979; Egardt, 1980] are another class of controllers whose parameters can be varied at run time to track the changes in the operating point. Here, periodic identification of the process and controller tuning is required in order to follow the changes in the plant dynamics [Aseltine, Mancini & Sarture, 1958; Narendra & Valavani, 1979; Kurz, Isermann & Schumann, 1980; Egardt, 1980; Astrom & Wittenmark, 1995; Poulin et al., 1996; Quevedo & Escobet, 2000; Astrom & Hagglund, 2001]. The degree of autonomy of a controller is closely related to the range of operation of the controller and consequently to its robustness. The degree of autonomy of a gain-scheduled controller is higher than that of a fixed controller but lower than that of an adaptive controller whose range of operation is correspondingly greater. There are many situations in practice where, due to unforeseen changes in the controlled plant and its operational environment, a greater degree of autonomy is required.

Limitations of the conventional control techniques have led to an extensive search for advanced control techniques which offer high autonomy and robustness despite the unfavourable operating conditions, uncertainty and vagueness that characterize the plant and its environment. This is typically the domain of industry and manufacturing. Coincidentally, this is also the domain of IC. This recognition was not long in coming and it was not long before the beneficial results of applying IC to industry became evident [Antsaklis, Passino & Wang, 1989; Astrom, Hang, Person & Ho, 1992; Passino, 1993; Passino, 1996; Zumberge & Passino, 1998; Kuswadi, 2001]. Many industrial processes are so complex that any attempt at describing them analytically is often futile [Astrom & Wittenmark, 1971]. Even if much effort is expended in determining some form of explicit model, it is usually too complex as to make it of little use for the design of a suitable controller. To apply control design techniques it is necessary to simplify the model through linearization and then model reduction before proceeding to determine an appropriate linear controller. The design procedures often used in design exercises leave much to be desired in practice, as the original control problem is no longer attacked. Instead, some idealized controller for
an idealized plant is determined and the probability that this controller is applicable to the real problem is small indeed. Invariably resort has to be taken to parameter tuning on-line in order to obtain acceptable performance. Techniques for designing and analyzing nonlinear plants are virtually non-existent. The limited techniques available are applied to very restricted situations. Thus the designer invariably falls on simulation to design an acceptable controller which must then be tested exhaustively in the field, an iterative, time-consuming procedure.

3.5 Intelligent control

The need to maintain tight production and quality control in large-scale industrial and manufacturing plants producing products with high specifications, and the inability of conventional control techniques to satisfy these requirements, has led to emergence of a new class of control techniques called IC. The reproduction of the cognitive and decision making processes of a human operator of an industrial plant executing his control task has been the subject of intense research since the 1950s [Kalman, 1958], reaching fruition in the 1970s with the implementation of the first experimental rule-based control system. The first practical unconventional industrial controllers were commissioned in the early 1980s in the cement industry, an industry with many difficult problems particularly in the critical kilning process. The development of unconventional controllers since then has been very rapid and they are to be found today not only in most process industries but in all kinds of household appliances as well [Kuswadi, 2001]. In this new class of controllers, the primary objective is minimization of the uncertainty and vagueness with which industrial processes are shrouded, leading to controllers with high autonomy and robustness. Therefore, these methods have caused considerable interest in industrial and manufacturing domain and have led to innovative controllers which have been applied to many complex problems in industry.

During the past two decades or so, a number of unconventional control techniques have evolved, offering solutions to many difficult control problems in industry and manufacturing. This has been possible because of the availability of powerful computers. Significant research has been
carried out in understanding and emulating human intelligence while, in parallel, developing inference engines for processing human knowledge. These techniques incorporate notions gathered from a wide range of specialization such as neurology, psychology, operations research, conventional control theory, computer science and communications theory. Many of the results of this effort have migrated to the field of control engineering and their fusion has led to a rapid growth of new techniques such as inductive reasoning, connectionism and parallel distributed processing for dealing with vagueness and uncertainty.

IC techniques that emulate characteristics of biological systems offer opportunities for creating control products with new capabilities. In today’s competitive economic environment, these control techniques can provide products with the all-important competitive edge that industry seek. However, while numerous applications of IC have been described in the literature, few advance past the simulation stage to become laboratory prototypes, and only a handful made their way into products. The ability of research to impact products hinges not so much on finding the best solution to a problem, but on finding the right problem and then solving it in a marketable way [Chiu, 1997]. The study of intelligent control systems requires both defining some important expressions that clarify these systems, and also understanding the desired application goals. The following definition shows the considerable challenges being faced by the developers of IC systems. Intelligence is a mental quality that consists of the abilities to learn from experience, adapt to new situations, understand and handle abstract concepts, and use knowledge to manipulate one’s environment [Encyclopedia Britannica, 2009]. One can also define AI as the ability of a digital computer or computer-controlled robot to perform tasks commonly associated with intelligent beings.

Thus, IC is designed to seek control methods that provide a level of intelligence and autonomy in the control decision that allows for improving the system performance further. As a consequence, IC has been one of the fastest growing areas in the field of control systems over the last two decades. Even though IC is a relatively new technique, a huge number of industrial
applications have been developed. IC is based on tools that emulate the biological behaviour that could solve problems as human beings do. The main tools for IC can be listed as:

a. **Fuzzy logic system**: The theory of fuzzy logic provides a mathematical morphology to emulate certain perpetual and linguistic attributes, associated with human cognition. It aims at modeling the inexact modes of reasoning and thought process, that play an essential role in the remarkable human ability to make rational decision in an environment of uncertainty and imprecision. Since fuzzy logic was first presented by Prof. Lotfi A. Zadeh, the number of fuzzy logic control applications has increased dramatically. For example, in a conventional PID controller, what is modelled is the system or process being controlled, whereas in a Fuzzy Logic Controller (FLC), the focus is the human operator’s behaviour [Mamdani, 1977]. In the PID, the system is modelled analytically by a set of differential equations, and their solution tells the PID controller how to adjust the system’s control parameters for each type of behaviour required. In the fuzzy controller, these adjustments are handled by a fuzzy rule-based expert system, a logical model of the thinking processes a person might go through in the course of manipulating the system. This shift in focus from the process to the person involved changing the entire approach to automatic control problems [Schwartz & Klir, 1992]. The search has been ongoing for a universal controller, of a ‘black box’ type, which can be simply plugged into any plant, where control is desired; thus, the controller takes over from there and sorts everything else out [Field & Wilhelm, 1981].

b. **Artificial neural network**: Artificial Neural Network (ANN) attempts to emulate the architecture and information representation schemes of the human brain. Neural networks have a varied history, progress having remained stagnant until the mid-1980s when efficient training algorithms were developed and fast computational platforms became readily available. Since then, neural networks have had a remarkable resurgence, being successfully used in a wide range of applications such as communications, speech analysis and synthesis, pattern recognition, system identification and control [Lin & Lee, 1991; Shen, 2001]. The technique of intelligent control using
ANN appeared only at the end of the 1980s.

c. **Evolutionary methods**: These are based on evolutionary processes such as natural evolution. GAs and evolutionary strategies (particle swarm intelligence, ant-colony method, biomimicry and simulated annealing etc.) are optimization techniques that attempt to avoid being easily trapped in local minima by simultaneously exploring multiple points in the search space and by generating new points based on the Darwinian theory of evolution - *survival of the fittest*. For example GA provides an adaptive, robust, parallel and randomized searching technique where a population of solutions evolves over a sequence of generations, to a globally optimal solution. EC methods, an outgrowth of evolutionary computing emerged as a viable method for optimum control appeared in mid 1990s. This technique has become possible only because of the rapid developments in computer technology. Since the early 1990s a major effort has been underway to develop derivatives of these techniques in order to exploit the best features of each in the design of IC. These new techniques have revolutionized the field of control engineering, offering new hope in solving many of the difficult control problems of industry and manufacturing. CI uses numerical representation of knowledge in contrast to AI, which uses symbolic representation. This feature is exploited in control engineering, which deals with numerical data since control and controlled variables are both defined numerically. CI adapts naturally to the engineering world, requiring no further data conversion. The techniques of CI share following general properties: (i) use a numerical representation of knowledge, (ii) demonstrate adaptability, (iii) have an inherent tolerance to errors, and (iv) possess speeds comparable to those of humans.

d. **Predictive methods**: These are mathematical methods that provide information about the future system behaviour.

   IC is the domain of SC, which focuses on stochastic, vague, empirical and associative situations, typical of the industrial and manufacturing environment. IC (sometimes termed as soft controllers) is a derivative of SC, being characterized by their ability to establish the functional
relationship between their inputs and outputs from empirical data, without recourse to explicit models of the controlled process. This is a radical departure from conventional controllers, which are based on explicit functional relations. Unlike their conventional counterparts, intelligent controllers can learn, remember and make decisions. IC, whatever form they may take, share the following properties: they (i) use the same process states (ii) use parallel distributed associative processors (iii) assure generality and (iv) are capable of codifying and processing vague data.

The 1990s was an era of new computational paradigms. In addition to fuzzy logic and neural networks, this third nonconventional computational paradigm has also become popular, which includes GA, evolutionary strategies and evolutionary programming. To distinguish them from the conventional methodologies based on precise formulations, Zadeh introduced the term SC in the early 1990s. Figure 3.3 shows various branches of computational intelligence.

![Figure 3.3: Branches of computational intelligence.](image)

Fuzzy logic, ANN and GA have grown into three distinct disciplines with the aim of designing intelligent systems for scientific and engineering applications. Each one of the above methods has advantages and disadvantages. Researchers felt the need of integrating these techniques to enjoy the merits of different biologically inspired methods into one system yielding several hybrid paradigms. As an example, in the case of fuzzy logic, one can combine this method with neural networks to obtain a neuro-fuzzy system. For instance, the Adaptive Neural Based
Fuzzy Inference System (ANFIS) was proposed in order to utilize the best part of fuzzy logic inference using an adaptive neural network topology [Jang, 1993]. Different authors have presented many hybrid systems [Karr, 2003], but the most important and useful combinations ones are: ANN combined with GA [Van, 1996], Fuzzy systems combined with GA [Sanchez, Shibata & Zadeh, 1997; Goonatilake, & Khebbal, 1996], Fuzzy systems combined with ANN [Kosko, 1992; Medsker, 1995]. The Various combinations of neural networks, genetic algorithms, and fuzzy logic help people to view them as complementary [Arzen, 1989].

![Figure 3.4: Basic sets for obtaining an IC system](image)

Although IC is more complex in structure than the PID controller, the IC gives a better response if the system changes to a different operation point. It is well known that linear systems are designed for working around the operation point. In the case of IC, one is able to design controllers that work outside the operation point. A global position in control theory of IC is shown in Figure 3.4, in which different sets intersect in the IC area. As it is presented, IC systems are in contrast to analytical control, because SC methodologies mimic consciousness and cognition in several important ways: (i) to learn from experience, (ii) to be able to universalize into domains where direct experience is absent, (iii) to run into parallel computer architectures, which simulate biological processes, and (iv) to perform mapping from inputs to the outputs faster than inherently serial analytical representations. The trade off, however, is a decrease in accuracy. If a tendency towards imprecision can be tolerated, then it should be possible to expand the range of the
applications even to those problems where the analytical and mathematical representations are readily available [Zilouchian & Jamshidi, 2001].

Saridis’ principle [Saridis, 1989; Saridis & Kimon, 1989], on which a number of successful intelligent hierarchical process management and control systems have been developed can be paraphrased as: “Increasing/decreasing precision is accompanied by decreasing/increasing intelligence”. An intelligent system involving clusters of intelligent controllers is expected to support: (i) Correctness - the ability to operate correctly for specific sets of commands and plant safety constraints. (ii) Robustness - the ability to operate acceptably despite wide variations in plant parameters. The higher layers of the hierarchy must possess an inherent ability to deal with unforeseen variations. (iii) Extendibility - the ability to accept extensions to both hardware and software without the necessity for major modifications to either. Extendibility implies modularity, which is the partitioning of the system into easily modifiable software and hardware modules. (iv) Reusability - the ability to use the same software in different applications. To possess this feature, the system must be general or possess an open architecture.

3.6 Intelligent control in industrial applications

The number of industrial applications that use IC systems is rapidly increasing, where one can find IC systems in both large and small industrial applications [Yen, Langari & Zadeh, 1995]. Another growing area of IC applications is developing household appliances, which are small but complex control systems. Many systems that use fuzzy logic or ANN for control apply these techniques to solve problems that fall outside the domain of conventional feedback control, e.g., in the case of a washing machine it is easier to control the duty cycle by a FLC than a PID controller. When one views fuzzy or neural control as only a non-linear counterpart of conventional feedback control techniques, the possibilities of using IC are reduced. Thus, a narrow conceptual view of IC system application leads to designers not appreciating or recognizing new areas of opportunities. If one uses only the IC systems as a conventional controller the difference is quite small. For instance,
using a FLC as a PID controller with the error and the change in error as inputs, the fuzzy controllers look similar to the conventional PID controller except that fuzzy control provides a non-linear control law. Another case is the use of an ANN applied to the set-point regulation problem, usually by replacing a conventional controller’s law and/or plant model with an artificial neural network. However, IC systems can handle high-level control systems. The control system of the train developed in Sendai, Japan by M/S Hitachi is such an example. Here fuzzy logic was used to select the notch position that will best satisfy the multiple, often-conflicting objectives. An additional example is that many Japanese companies such as M/S Matsushita, M/S Sanyo, M/S Hitachi and M/S Sharp have incorporated ANN technology into a product known as the kerosene fan heater. In Sanyo’s heater, ANN learns the daily usage pattern of the consumer, thus allowing the heater to automatically start to preheat in advance [Warwick, 1998]. For many industrial applications one could complement the conventional controllers by an IC generating a new one, rather than using IC alone. The industrial challenge is focused on developing control systems that are capable of adapting to rapidly changing environments and on improving their performance based on their experience. In other words, modern control systems are being developed that are capable of learning to improve their performance over time (to learn) much like humans do [Karr, 2003].

3.7 Chapter summary

This chapter has reviewed the fundamentals of the PID control technique. Its development, implementation methods, tuning procedures and limitations are reviewed in detail. The requirements of the IC techniques are introduced for control of the complex systems where PID finds its limitations. Various technologies of ICs are introduced as effective alternative to PID for control of complex systems. Some applications of the IC in industry were also summarized.