CHAPTER 1 INTRODUCTION

Control systems exist in human society from ancient years of civilization. The advancement of control system has played a dominant role in modernization of modern civilization. Control systems find vast applications which are not only limited to industry but every aspect of modern living from a simple flush tank to a complex spacecraft. Control system itself has evolved from classic control to modern control which is widely based on computers and utilizes various computing techniques. Fuzzy logic control is one such example of modern artificial intelligence based control technique. The current research looks forward to improve a key aspect of fuzzy logic based control system. The algorithm of which is discussed in subsequent chapters along with some real-time implementation examples.

1. 1 CONTROL SYSTEM

Control systems are an essential millstone of current society. From ancient world to modern world several applications can be ascertained surrounding our world: a trivial flush tank water filling system used in daily life, an industrial robotic arm performing a repetitive job, a power plant automatically maintaining power generation according to the demand, engine firing in a rocket, a satellite maintaining its orbit.

The automatically controlled systems are not only man-made; but they do exist in nature too, from which the inspiration was drawn. Within a human body lie several control systems, for instance the pancreas, which regulates our blood sugar level. Adrenaline rush along with increase in our heart rate during exercise/adventure, delivering more oxygen to be to our muscles groups. Motion tracking by our eyes; to a simple reflex action controlled by our neurons.

Control systems are used primarily for decision making i.e. providing autonomy to a dynamical system. Definition: A control system is a system or arrangement of systems arranged in a manner to regulate (control) output of another system (another system) [1]. Figure 1-1 below illustrates block diagram for a trivial control system.

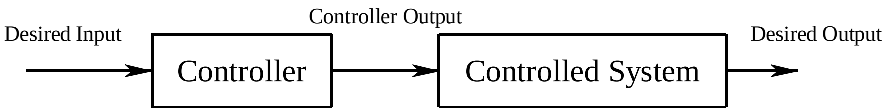

Figure 1-1 Elementary (open-loop) Control System

The principle objective of designing a control system is to obtain a desired output for a given specified input parameter. All the practical systems are associated with some kind of error that needs to be minimized in order to achieve our goal of obtaining desired output. A feedback controller (Figure **1-2**) compares the reference set-point with the measured value of the controlled parameter in order to calculate the error (deviation from the desired value) and takes the control action to eliminate the error. The transient and steady state response of a feedback system can be easily controlled by adjusting the gain of system under consideration or designing a suitable controller. Thus a closed loop system measures and applies corrective action to the system [2].

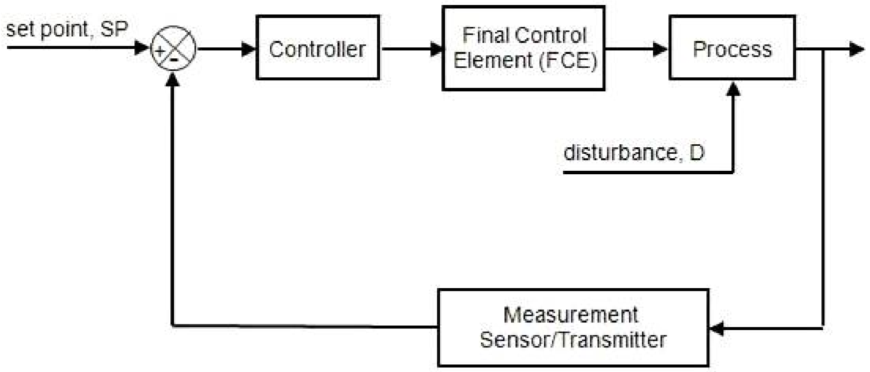

Figure 1-2 Feedback control system block diagram

The conventional controllers are used commonly in industries to control industrial processes. Their popularity grows due to their robust performance over wide range of operating points and simplicity in their functionality. However these controllers are designed for linear systems and hence cannot be implemented for nonlinear systems. The conventional approach for nonlinear system controller design is to linearize the system equation around the operating point (steady state) and then applying linear controller design rules. However a dip in controller performance is observed as process moves away from the designated operating point around which it was linearized. The conventional controllers cannot be implemented with the systems involving fast change in parameter with time domain that is not suitable for time variant systems. Also with the advancement in technologies the complexity of system has increased and for solving unsuspected uncertainties of these complex systems some sort of advanced control strategy is needed in order to obtain desirable performance [3].

The world war demanded new feats in control system engineering for accurate control of ballistic weapons and modern communication devices. This led to the widespread adaption of the state-space control techniques. The classical control techniques which were based on frequency response and root locus design techniques were replaced by state-space control methods. The state-space technique is also applicable for control of non-linear and multivariable systems [4]. However the applicability of state-space methods again depends on the accurate estimation of mathematical model of the system under study. The development in process industries and aerospace applications necessitated the adjustment of controller gains to be an online task rather than a laboratory/design task. This led to the dawn of adaptive control. The philosophy of adaptive control is the continuous adjustment of controller gains via a tuning algorithm which constantly evaluated the controller performance based on the dynamic model of plant and the controller gains are updated so as to achieve optimized controller performance [5]. However these control algorithms again rely extensively on the accurate estimation of plant dynamics.

1. 2 INTELLIGENT CONTROL SYSTEM

Intelligent control (soft computing based) system emulates characteristics of naturally occurring systems, examples of such techniques includes: fuzzy logic based control systems(FLC), artificial neural network (ANN) based learning techniques, genetic algorithms (GA) based optimization, particulate swarm based optimization (PSO), back propagation algorithm or machine learning and integrating these with automatic control systems. Such a controller is capable of driving complex systems automatically with higher degree of accuracy [6].

This is an era of advance technologies and current systems are getting replaced by more complex systems of higher accuracy and efficiency. And for these complex systems controlling is more challenging with the conventional controllers and hence more complex controllers are being introduced. As the complexity of the system increases their dynamic model is hard to realise due to the fact that controlling parameters are not well defined or may vary unexpectedly. In such a case the controlling of a system can be achieved by intelligent control whose design is irrespective of mathematical modeling of the system to be controlled. An intelligent control is capable of acting appropriately in uncertain conditions where the probability of success depends on proper actions. Intelligent control is able to sense the working environment of the plant and is able to make decisions and controlling actions. The intelligent systems use a knowledge base to remove the uncertainty of the system and automatically assign the controlling actions. An intelligent control is designed to obtain desirable functionality under changing conditions with high degree of automaticity. Adapting changing working conditions is an important characteristic of an intelligent control system and without any external intervention it can deal with unanticipated disturbances or noise of a plant autonomously with higher degree of accuracy compared to the conventional feedback controllers. [7]

For lower degree of autonomy intelligent control is not required and conventional controllers can be useful however for higher degree of autonomous behaviour intelligent system is essential. In order to deal with complex and incomplete structure the control system should have a well-defined architecture to efficiently analyse and evaluate control strategies. Mechanism for representing knowledge can be varied and may include state space variables, attributed value pair and statements. Learning/Estimating controller parameters from previous experimental/simulation results is required in order to attain fast response, to be relived from routine tasks. Intelligence is not the behaviour and is the internal property of the system and by passive observations of behaviour the system intelligence cannot be determined thus it can be concluded that intelligent control system are meant for highly complex and unpredictable systems and can be implemented on a plant after carrying outer series of tests on a plant.

The intelligent control is a multidimensional field in which control algorithms are developed by imitating certain characteristics of intelligent biological systems. The intelligent control is a combination of mathematical modeling, linguistic approaches and algorithms applied to various processes and system. With advances in human understanding of biological systems various methods of intelligent control have been introduced, such as ANN, GA, PSO, FLS and many more.

Each of the above method has its own area of application. For example **artificial neural network** is a field that is been very popular for forecasting/prediction applications. This technique involves the emulation of low-level biological functions of brain to perform the controlling task by forming sets of neurons that forms a biological network. The interconnected neurons form a multilayer perception. These neurons are then trained regardless of the type of network they form. For example: these can be used to predict and manage space between parked vehicles in an automatic parking guidance system. A neural network can be trained to learn on how to regulate the space between cars of a parking area by continuously providing the examples on performing task correctly. Once training is completed a neural network based system can be implemented on a car to regulate the inter car spacing by recollecting input for every value of distance and sensing the rate of change of this distance. However this method is model independent and provides with good accuracy [8].

Genetic algorithm is primarily an optimization technique based on characteristics of biological evolution, inspired from genetics and natural selection (survival of fittest). It is an optimised method that evolves the fittest population and performs parallel and stochastic search approach. Although this method does not require any mathematical modeling of the system but with modifications designer can effectively use such information when available. The objective of this method is to maximize the fitness function that measures the quality of solution for the problem to be optimized. A single entity is represented by a string and each member of a string is considered to be a gene and these genes combines to form a chromosome; where genes are the symbolic representation of the characteristics of corresponding entity. The chromosome represents the controller's parameters which are being optimized. These chromosomes are combined together to carry out crossover, the crossover converges the parameter to a satisfactory positions in order to find better solutions to the optimized problem. It inclines to perform a localised search around the fittest individual. After crossover, mutation is carried out which functions to explore the global maximum of the fitness function from the local maximum. Thus repetition of this process results in the evolution of a new population. After generating all the populations the one that maximizes the objective function is chosen as the optimized one [9].

Another advanced method for intelligent control is **particle swarm optimization** concentrating on behaviour of swarm of bees, birds, fish or other animals. It is a robust stochastic computational algorithm method based on the swarm movement looking for a fertilised location to feed. It involves the information sharing amongst the members of the population, and the profit obtained from the discoveries and previous experiences of various particles during the search for food is shared amongst all the particles [10].

Arousing from the concept of uncertainty Zadeh [11] proposed the fuzzy set (FS) theory in the 1960s. The primary notion of **fuzzy logic** was to deal with ambiguous, uncertain, or imprecise data. Till date there are several misconceptions about fuzzy logic. One of the major misconceptions is: "fuzzy logic is fuzzy and an unsystematic science"; instead fuzzy logic is a systematic (precise) technique for handling imprecision/vagueness. The concept of fuzziness is attributed to relative graded membership of FSs unlike fixed (0 and 1) membership value of a crisp set. This very notion is inspired by the phenomena of human cognition and decision making, which makes FLS capable to deal with information arising from linguistic and cognitive computation (uncertain, imprecise, vague, or partially true information). Fuzzy logic facilitates in the elimination of vague human assessments in computing problems. Fuzzy logic based systems have been used in numerous industrial/practical applications which many times include: pattern recognition (image processing), temperature control in air conditioners, washing machines, ABS (anti-lock braking systems), automatic transmission for automobiles, aviation applications (such as auto-pilot, UAVs), weather forecasting systems, business analytics (for new product pricing prediction, project risk management), medical diagnostic systems and machine assisted disease treatment plans, and stock market analytics to name a few. Fuzzy logic is often combined with other soft computing methods (GA, PSO etc.) to make intelligent systems for control, image processing, pattern recognition, optimization to name a few [12], [13], [14], [15], [16], [17].

A foremost attribute of a fuzzy logic system is its competence to handle imprecise/uncertain/incomplete systems. To design an efficient FLS mathematical model is not necessary; the system can be design if expert knowledge for the system is available.

1. 3 UNCERTAINTY AND FUZZY LOGIC

With the increase in complexity of a given system our proficiency to make precise and yet significant statements about its performance decreases until a threshold is reached beyond which both these attributes become almost mutually exclusive. As the system becomes more complex, uncertainty in the system arises in the form of ambiguity, impression, fuzziness, discord, vagueness [11]. In some complex system the available numerical data is less and mostly imprecise and ambiguous data is available, in such a case fuzzy reasoning may be useful in understanding the behaviour of system by incorporating between input and output situation [18], [19].

The imprecision and incompleteness of the model of a real time system information leads to parametric uncertainty and systems of this kind are not easy to control. In order to overcome this problem the fuzzy logic based controllers can be employed in which parameters of a plant are given as an input to fuzzy controller. Fuzzy control of such system relies on the model of the plant but due to uncertainty in parameters the parameter can take any value inside the bounded range if the parameter is associated within a limit of tolerance. The nature of the uncertainty can be described as fuzziness which is result of imprecise boundaries (multivalued membership function) of a FS (Fuzzy set). Fuzzy logic is helpful in solving the problem associated with a nonlinear system through projection and extension principles and the conclusion can be derived from the use of fuzzy systems [20].

The expert system comprises of meaningful information stored in its knowledge base, and based on the information stored in its knowledge base it provides answers to the users. The knowledge base of an expert system is a collection of proposition that depicts the facts and conditional proposition constitutes the rules. Designing an expert system is a challenging task as the information available may not be complete or fully reliable or may be imprecise in nature, in such a case the resulted uncertainty needs to be managed in order to design a knowledge based expert system. L.A Zadeh [21] proposed a method based on using fuzzy logic underlining approximations and fuzzy reasoning. The fuzzy logic provides a necessary framework to deal with linguistic quantifiers such as few, many, more, too, most, not many, almost all, about etc.

Any uncertainty in the knowledge base information leads to uncertainty in the derived conclusion from the premises, making the expert system inapplicable. Designing of an expert system is a challenging task wherein the designer needs to ascertain the reliability of the acquired data. The architecture of expert system should analyse the uncertainty arising at premise, and conclusion should be associated with certainty factor. The computation of this certainty factor can be carried out through fuzzy logic that is the fuzzy logic approach can be used to deal with possibility and probabilistic uncertainties. Employing fuzzy logic to manage uncertainty can be helpful in dealing with issues such as the fuzziness of antecedents and consequents in formation of rules, partial matching between the information provided by the user and antecedent of a rule and the incidence of fuzzy quantifier in the rule base of fuzzy system.

1. 4 FUZZY LOGIC BASED CONTROL SYSTEM

With the advancements in theory of fuzzy logic, FLC has found its use in several practical applications [18], [22], [23], [24]. FLC based system is a nonlinear mapping between input and output variables i.e. they are utilized for inferring complex nonlinear systems. The nonlinear mapping property of FLC is predominant when the physical mechanism to be controller is inherently nonlinear (primarily due to parametric uncertainty or time variant systems) [25]. The working principle of FLC is different from conventional stochastic models. FLCs do not make presumptions regarding to the process based on the probability distribution model. This distinction of FLC makes them particularly applicable for nonstationary systems. Also, FLCs can uniformly approximate any real continuous function on a compact set. This ensures the applicability of a FLS for approximating a given function to any degree of accuracy [26].

Model based system design approach utilizes the simplified mathematical models of the dynamical system under observation for engineering design [27]. However this approach does not involve operational knowledge of the concerned dynamical systems but consider only the mathematical/physical aspects of the system. On the contrary FLC based dynamical system modeling utilizes both these attributes: mathematical model, knowledge base for the system [28].

The control surface/decision surface is obtained from a FLC is a non-linear trajectory (dynamics) of controller in an n-dimensional space (n being the number of I/O’s). With proper adaption techniques and tuning a controller can be trained to handle unmodeled dynamics present in the system [20]. The application of fuzzy logic in control system ranges from application of fuzzy system to classical PID control [29], multi-input, multi-output controls (MIMO) to modern control systems such as statistical process control [30].

Fuzzy logic control system can directly handle uncertain and imprecise data as compared to conventional (non-intelligent) control techniques, i.e. FLCs gives better results in the presence of uncertainties such as: 1.) disturbance, and 2.) measurement uncertainties.

1. 4. 1 STRUCTURE OF A FUZZY CONTROLLER

Most of the practical applications of fuzzy logic are in the form of FLC. There are numerous consumer products in today's market which employs fuzzy logic [20]. The design of a FLC primarily involves utilization of fuzzy I/O sets. By definition: if a system can be termed as a fuzzy logic based system if it utilizes FSs at least one of input or output variables. Hence to control a process by fuzzy logic the first step is to replace the controller of Figure 1-2 is with a fuzzy logic based system, structure of which is given in Figure 1-3. Here at least one of the I/O variables should be FS. However for most practical cases both the I/P and O/P variables are fuzzy.

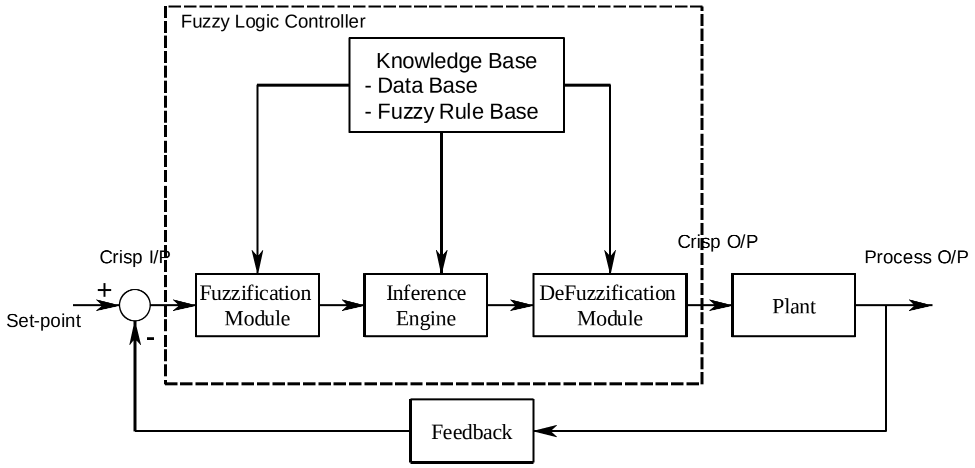

Figure 1-3 Fuzzy logic based control system – block diagram [3]

First – generation simple fuzzy controllers are represented by the block diagram stated in Figure 1-3. Real world is crisp, and FSs do not occur in real world. Hence the first step is to convert input crisp data into fuzzy data. The input stage consists of a fuzzification module; here the fuzzification method is determined by the knowledge base (designer specific). This knowledge base consists of all the fuzzy partitions (predefined sets). The inputs are then classified into one of the sets depending on instantaneous conditions. Once all the I/O FSs are defined the next step is to obtain the instantaneous output from the fuzzy logic system. This is done by the inference engine module, which consists of a predefined rule base and output calculation method. Depending on various conditions single/multiple rules fire and the output is calculated. The output form the inference engine is fuzzy. This output needs to be converted to a crisp logic which can interact with real world. This is done with the help of defuzzifier. The knowledge base contains all the defuzzification methods, and depending on the user configuration a particular defuzzification method is utilized. The steps involved in designing a simple fuzzy control can be summarized as follows [20]:

- Identify of variable which needs to be converted in FSs (inputs, states and outputs).
- Formation of FSs (defining the universe of discourse, set partition, linguistic assignment)
- Formulation of rule base connecting various input and output variables,
- Fuzzify the instantaneous inputs (I/P and O/P variables) to the FLC.
- Combine the fuzzy I/O sets and rules to infer the output contributed from each fired rule.
- Compute the output generated by combining each rule to a single fuzzy output.
- Defuzzify the obtained fuzzy output to get a crisp value.

The inputs given to the fuzzy controller are often crisp rather than linguistic. The preprocessor according to measurement standards conditions the input before it enters the controller. Fuzzification is the first block of fuzzy controller; its function is to convert input data into degree of membership by referencing the available membership functions (MFs). Each input is associated with a membership value for linguistic term. The rule base is a set of rules with several variables at the condition and conclusion of rules. The inputs to the controller are error, change in error and accumulated error formed from error measurement. In rule base it is assumed that a process output is regulated around a predefined reference or set point. The inference engine determines how well the fuzzy logic is based operation performed and with the knowledge base determines the output of each fuzzy rule. It looks up for the value of MF associated with each rule of rule base. The fuzzy output is converted to crisp value with defuzzifier so that it can be used to drive real-world devices. The most popular method is center of gravity method. The crisp control action is required in practical applications. At post-processing the scaling of the output is done in order to convert it to the required standards.

A number of assumptions are implicit in a fuzzy control system design [20]. Some of which restrict the applicability of fuzzy systems are:

1. The first and foremost is the existence a body of experts which can formulate a set of I/O measurements data set of linguistic rules, engineering common sense, intuition, from which knowledge base and fuzzy rules can be extracted – although these set of rules/knowledge base may differ from expert to expert [31] or may be different for same systems but with given different ambient conditions.
2. A solution exists – whereas in modern day competition industries not only require a good enough solution but an optimum solution.

The knowledge base supporting the fuzzy logic is prone to uncertainty and vagueness. There are four common ways in which uncertainty can occur in a FLS [32]:

1. Linguistic variables (words) for naming variables, rules can mean different things to different people (experts).
2. Consequents (connector between input and output fuzzy variable) obtained by poll from a group of experts are generally different for the same rule since the experts will not necessarily be in agreement.
3. Measurements system may be noisy and therefore uncertain causing the uncertainty in the measured variables.
4. Noisy training data.

1. 5 ENTROPY FUNCTION AND OPTIMIZATION

One of the prominent mathematical characteristic of FS employed for formulation of objective function is “fuzzy entropy” function. This will be emphasized more in the next chapter (literature review). Entropy is a measure of fuzziness in a given FS or system as degree of randomness, and the uncertainty can be used as information measure. Thus measurement of quantity of information obtained from FS or fuzzy system is called as fuzzy entropy. In other words, it indicates about the uncertainty linked with a variable due to associated randomness. Al-Sharhan et al [33] summarized a concise review of various mathematical formulations used for describing fuzzy entropy. Authors also postulated the formation of fuzzy entropy from classical Shannon entropy depicting significance of various representations used to formulate fuzzy entropy. The fuzzy entropy function using the Shannon's function can be written as [34]:

$$H(A) = -\int_{-\infty}^{\infty} \{\mu_i \log \mu_i + (1-\mu_i)\log(1-\mu_i)\} \qquad (1\text{-}1)$$

here $\mu_i$is the membership value for any element i in a FS A, and can be rewritten as:

$$H(A) = \int_{-\infty}^{\infty} f\big(\mu(x)\big)dx \qquad (1\text{-}2)$$

here $f(x) = -xlogx - (1-x)\log(1-x)$

The primary objective of this research is to formulate an algorithm to obtain optimized MF for FSs. One of the elementary challenges faced by researchers in designing a FLC is finding optimal FSs [35]. As there is no "tuning algorithm" or systematic procedure to design FS, researchers seek to optimize their FS choice by evaluating various objective functions. Developing an objective function may be tough task for beginners as it may lead to a non-applicable fuzzy system. The framework proposed in this research aims at forming a guideline for defining an objective function which can be applied at any designer proficiency (beginner/intermediate/expert) and can be combined with almost any optimization technique [36].

1. 6 CONTRIBUTION OF THIS RESEARCH

The objectives of this research are:

- ✓ To formulate an algorithm to obtain optimized membership function in FSs using fuzzy entropy as an evaluation parameter.
- ✓ To Test the applicability of the developed algorithm for a class of non-linear systems.

- Benchmark Non-linear system – Swing up stabilization for an Inverted pendulum [37]
- Non-linear system with cross-coupling – Pitch and Yaw angle control for a twin rotor MIMO system [38]
- Non-linear system with significant uncertainty – Magnetic levitation of a steel ball [39]

1. 7 ORGANIZATION OF THESIS

The dissertation comprises of 6 chapters. Chapter 1 presents the introduction to control system, intelligent control system and FLCs. The role of fuzzy logic in dealing with uncertain systems is presented and a brief introduction of FLC is also discussed. The significance of fuzzy entropy function with respect to the proposed optimization algorithm is also discussed.

Chapter 2 summarizes the key developments in FLC with reference to the proposed work, and scope of the proposed research. Theoretical background for fuzzy entropy function has been discussed along with various applications. Finally the objective function for proposed work is formulated along with the optimization.

Chapters 3, 4 and 5 depict the detailed study of the Twin Arm Inverted Pendulum, Twin Rotor MIMO system, and Magnetic Levitation system respectively. The validation of simulated models along with the available real-time models has been discussed concisely. These chapters emphasis on the FLC architecture utilized for controller design of the respective systems. The architecture covers the designed controller along with the I/O fuzzy sets. The results for the proposed controller are compared with reference work and inferred to understand the advantages of the proposed approach. Finally chapter 6 concludes the proposed research and future scope have been identified.