Abstract

Fuzzy logic is one of the most popular technologies now days prominently used in the all branches of technology, from medical sciences to the automotive controls. The aim of this paper is to present an overview of the fuzzy logic based control and its basic difference to the conventional control theory. The paper describes the basic principles of fuzzy logic, different definitions and complete procedure of the fuzzy based control implementation which is also explained with suitable examples. The paper also presents a brief overview of the practical applications of the fuzzy control theory.

Keywords

Fuzzy Logic, Fuzzy set, Fuzzy control

1. Introduction

Fuzzy logic (FL) is one of the fields in Artificial Intelligence (AI) which has gained importance and popularity over last decades. Fuzzy Logic was first time proposed by Lotfi Zadeh in 1965 [2], while developing theory of fuzzy sets. Fuzzy logic is form of multi valued logic. It deals with reasoning that is approximate rather than fixed or exact. The base of FL is fuzzy set which is basically a prolongation of classical set. Fuzzy Logic is different from traditional logic as it represents human thinking and natural language. In traditional logic, element in the binary set has two valued logic- true or false (0 or 1), which indicates either the element is completely belongs to the set or not. Partial membership concept is not present in traditional set theory, it has black and white concept only where less ambiguity is expected [3]. In real world, we have more ambiguities, vague concepts which humans feel easy to communicate and understand. In conventional mathematics or in set theory, it is difficult to handle these concepts in rational way. Fuzzy logic can deal with these real world ambiguities and fuzziness. As numerical models cannot handle all these ambiguities since they make the nonlinear or complex systems unfeasible, whereas fuzzy modeling provides best alternative under such circumstances. Fuzzy logic has applications in many fields ranging from control, automation technology, robotics, image processing, pattern recognition, medical diagnosis etc.

The paper is presented in following manner. The next section presents the basic principles of the fuzzy logic, linguistic variables and fuzzy granulation. The fuzzy set and basic operations of fuzzy sets are defined in section 3. In section 4 and 5, the fuzzy rules are described and a brief overview of the complete fuzzy control decision making is presented. The section 6 gives overview of the applications of fuzzy logic in various fields, followed by the conclusion.

2. Fuzzy logic, linguistic variable and granulation

As Zadeh proposed [2]-[3], Fuzzy logic can be used in two different views; one is in narrow view, fuzzy logic, as it is based on multi-valued logic, concentrates on approximate reasoning. Although fuzzy logic is rooted on multivalued logic, it has some contradiction with traditional multivalued logical system e.g. Lukasiewicz’s logic [3]. Similarly, the concepts which made fuzzy logic effective in approximate reasoning are also not from the traditional multivalued system. These are linguistic variable, canonical form, fuzzy rule, fuzzy graph, and fuzzy quantifiers. The second approach of looking at fuzzy logic, i.e. in broad view, is almost equivalent to fuzzy set theory. Fuzzy set theory is quite vast. Actually fuzzy logic is one of the branches of fuzzy set theory; other branches are fuzzy arithmetic, fuzzy mathematical programming, fuzzy topology, etc [3].

Linguistic variable plays important role in applications of fuzzy logic. Fuzzy logic as it makes it easy to understand and interpret the physical variables, i.e. linguistic variables, to be processed in simple way. Linguistic variables are nothing but variables with values of words [1][3]. For example, “height” is linguistic variable with values “short”, “tall”, “very tall”. “Age” is linguistic variable with values “young”, “old”, “not very old” [4][6][10]. In the universe of discourse of fuzzy set, these values are used as label to the fuzzy sets. Each fuzzy set can be defined by its membership function e.g. $\mu_{\text{old}}(u)$ which associated with numerical value $u$. The degree of membership will take value in the interval [0, 1].

![Granulation and data compression][1]

If we consider linguistic term “young” and take numerical value “25”, then here “25” is simpler than the function “young”, but “young” is one of the value from three parameters say “young”,

[1]: https://example.com/granulation-data-compression.png
“old”, “not very old”, whereas “25” is one of the values in “100” values. From this example, the linguistic values can be used as one of form of data compression which is further suggested to consider as fuzzy granulation [3].

Conventional quantization can achieve same results as fuzzy granulation but the interval is crisp interval in quantization, which shows sudden changes in result whereas in fuzzy granulation due to overlapping fuzzy interval there will be gradual transition from one value to another.

![Quantization vs. granulation](image)

In many applications of fuzzy control theory, member function of linguistic values are consider to be trapezoidal or triangular in shape as shown in following Figure 3. The linguistic values are ranges from three to seven, and the values are labeled as positive small (PS), negative small (NS), zero (Z), Positive medium (PM), negative medium (NM), positive large (PL) and negative large (NL).

![Triangular linguistic values](image)

3. Fuzzy set

Fuzzy set is an extension of classical set. According to Zadeh fuzzy set is characterized by a membership (characteristic) function which assigns to each object a grade of membership ranging between zero and one [2].

**Definition:** A fuzzy set $F$ in a universe of discourse $U$ is characterized by membership function $\mu_F$ which takes values in the interval $[0,1]$, i.e. $\mu_F: U \rightarrow [0,1]$

If $U$ contains finite number of elements, fuzzy set $F$ can be denoted by:

$$F = \{ \mu_F(u_1)/u_1, \mu_F(u_2)/u_2, \ldots, \mu_F(u_n)/u_n \}$$  (1)

In classical set, member is either belongs to the set or not, but in fuzzy set, member has degree of membership, like they belongs to the set with certain degree. In fuzzy sets, membership ranges between 0 and 1. 0 means member does not belong to the set, 1 means member completely belongs to the set and any member in between means it partially belongs to the set. The traditional set follows Boolean logic; it has two propositions only 0 or 1 (or true/false). It is restricting to describe the concepts like “young” and “tall”. Consider the concept of “tall”[4][6]. In Boolean logic, it is difficult to quantify between “tall” and “short”. If we consider threshold height, say 6 feet as tall, then we can classify person with height 7 feet as “tall” and person with height 5 feet as “short”. But if we consider two persons with height 5’11” and 6’1”, respectively, then person with height 5’11” will be classified as “short” whereas other person with height 6’1” will be fall into the category of “tall”. This cannot be the right conclusion. The person with height 5’11” is shorter than person with height 6’1”, still there is minor difference in heights. Even if we increase or decrease the threshold, still the same problem will exist. As in Boolean logic, we need to categorize it one of the two groups only, “tall” or “short”. Even there is minor difference between two heights [6]. In fuzzy sets, we can handle this situation, by assigning “degree of membership” to each height. So the person with height 5’11” is tall with certain degree and person with height 6’1” is tall with another degree. Fuzzy set deal with different heights that can be “tall” to different degrees. Following Figure 4 represent fuzzy set “tall” [6].

![Representation of concept “tall” using fuzzy set](image)

3.1 Fuzzy set operations

As discussed earlier, fuzzy set is generalization of classical set (or crisp set), so these fuzzy set operations are generalizations of crisp set operation. Therefore, operations like union, intersection and complementation can be defined for fuzzy set using degree of membership of each element in respective fuzzy set. The operations called standard fuzzy set operations, are explained as below-

**Union:** Union of two fuzzy set $A$ and $B$ is given by taking the maximum of the degree of the membership of the elements in respective fuzzy set. The operations called standard fuzzy set operations, are explained as below-

$$ (A \cup B) (x) = \max \{A(x), B(x)\}$$ (2)

This is explained in figure 5.
**Intersection:** Intersection of two fuzzy set is given by taking the minimum of the degree of the membership of the elements in A and B.

\[(A \cap B)(x) = \min\{A(x), B(x)\}\]  
(3)

This is explained in Figure 6.

**Complement:** Complement of a fuzzy set A is obtained by subtracting from 1 the degree of membership.

\[cA(x) = 1 - A(x)\]  
(4)

This is explained in Figure 7.

**4. Fuzzy rules**

Fuzzy rules are used to express piece of knowledge in fuzzy logic. A fuzzy rule is a linguistic expression of causal dependencies between linguistic variables in form of if-then statements.

If \(X\) is \(A\) then \(Y\) is \(B\)  
(5)

where \(X\) and \(Y\) are linguistic variables and \(A\) and \(B\) are their linguistic values determined by a fuzzy sets on the universe of discourse \(X\) and \(Y\), respectively.

In fuzzy logic, fuzzy rules are used for decision making. Linguistic variables are used for the construction of language referred as FDCL (Fuzzy Dependency and Command Language) [3]. FDCL gives structure to estimated dependencies and commands using fuzzy if-then rules or simply fuzzy rules. FDCL, like other language define by its syntax and semantics, and they define form of rules and their meaning. The following example best describes the FDCL language [3].

1. If pressure is high then volume is small.
2. If pressure is high and temperature is low then volume is very small.
3. If pressure is high then lower temperature slightly.
4. If pressure is high then volume is small unless temperature is high.
5. If pressure is high then usually volume is small.

In this example, “pressure”, “volume” and “temperature” are linguistic variables and “small”, “low” and “high” are their linguistic values. These fuzzy rules in fuzzy logic, add subjective reasoning capabilities to machine intelligence, which usually based on two-valued logic. Which rules should be combined are based on the interpretation of single fuzzy rule.

**5. Fuzzy decision making procedure**

Mechanism of fuzzy decision making involves manipulation of fuzzy variable through linguistic equations or fuzzy rules. The below Figure 8 explains the whole mechanism.

**Fuzzification:** In fuzzification, membership degree is computed for each input variable with respect to its linguistic term.

**Rule matching:** In rule matching, the firing strength (degree of satisfaction) of individual rule are calculated.

**Fuzzy Inference:** The recommendation of rules according to firing strengths and rule conclusions are determined in fuzzy inference.

**Fuzzy Aggregation:** Fuzzy aggregation combines recommendations from individual rules into an overall implied fuzzy set.

**Defuzzification:** Defuzzification involves determination of a crisp value based on implied fuzzy sets derived from the rules, as final result or solution.

**6. Fuzzy system applications**

Fuzzy logic has wide area of applications, from control theory to medical diagnosis. In this section, two applications are discussed, followed by the brief overview of other applications of fuzzy system technology. First application described below is control of complex system. Almardy [8] used a fuzzy control system to apply electric current to a series of anodes to protect a long buried pipeline. The aim of the application is to establish proper protection as well as minimize the power used to protect the pipeline. Main problem is localized rain events,
due to which soil conductivity increases along the pipeline. Fuzzy control used as modeling the different soil conditions along the pipeline would be complex for a practical control system. The fuzzy control model was made with 3 anodes followed by 126 rules, which results in the controller having adequate performance in maintaining protection.

In another application for medical diagnosis and treatment support system, in which the support system present several difficulties such as linguistic description and lack of selectivity and sensitivity in medical test results. Fuzzy methods are used in the automation of this application. Using these methods, the medical result yield contains likelihood estimation rather than confirmation of presence or absence of disease. In practice, the recommendations for action suggested in guidelines are vague and conflicting. But these difficulties are well handled by the fuzzy methods [9][7].

One of the well known application of fuzzy logic can be referred as Hitachi’s first automated train operation for Sendai subway system in Japan that has been in daily operation since 1987. The train controlled by fuzzy predictive controller, which consume less electric energy and ride more comfortably than the case where the control was done by non-fuzzy controller. Another Hitachi’s product was group fuzzy control operation for elevator. In this application, the elevator which is used in rush hours, the fuzzy control could reduce the waiting time as well as idle time and also make the riding and stopping smoother as compared to elevators controlled by traditional controllers. The use of fuzzy control in consumer product was started from 1989, the first home appliance products which include fuzzy control were washing machines, these were fully automatic and washing cloths was much simpler for users. User had to press start button and machine was taking care of the rest of the task. It could automatically select the wash, rinse and spin cycles, and the result were more cleaner clothes and efficient wash cycle. Fuzzy processing was available on the chip which has made it feasible to use these chips within individual products. The product range was increased because of this, with fuzzy controlled rice cookers, vacuum cleaners and home climate control system [4][6].

The major application area is automotive industry. Most of the automotive manufacturers are pursuing fuzzy control concepts. Fuzzy control has been applied to control automatic transmission system, suspension system, engine system, climate system and antilock brake system. These systems are used to make the vehicle better, more efficient and safer to ride.

Many commercial products uses fuzzy system technology. It has been used to enhance processing of digital image and signals. The Canon camera’s autofocus system is the best example of the efficient implementation of fuzzy technology. The autofocus, autozoom and autoexposure systems for Minolta cameras use fuzzy controllers. Using fuzzy logic techniques, Sanyo and Canon camcorders are better in auto-white balancing system, autoexposure and autofocus system. Image stabilizer for camcorder of Matsushita has been implemented with fuzzy technology, fuzzy inference was also used to improve image quality. Because of Fuzzy system technology, electro-photography process of photocopying machine has been improved. The image quality of Sanyo copies has been improved by better toner supply control based on fuzzy control and Matsushita copies are also improved by better autoexposure fuzzy based control. Some other successful applications are hand written language recognition and voice recognition.

Like all other areas, fuzzy system technology has larger impact on healthcare industry. The biomedical applications are less due to inherent complexity and uncertainty of the systems as well as the risk involved. In biomedicine science, human knowledge, skills and experience are more important in diagnosis and treatment of diseases. This biomedical system is difficult to manage as it has time delay and nonlinearity. World’s first fuzzy control in medicine is drug delivery system, which was developed and implemented to regulate blood pressure in post-surgical open heart patients at cardiac intensive care unit (ICU). Some other applications include determining the disease risk using fuzzy expert systems, medical control system, determination of drug dose. To control muscle immobility and hyper tension during general anesthesia, assessment of cardiovascular dynamics during ventricular assistance, diagnosis of artery lesions and coronary stenosis, support for seriognosis, intelligent medicile alarms, fuzzy control system has been applied. Classification of tissue and structure in electrocardiograms, classification of normal and cancerous tissues in brain magnetic resonance image are the other successful application of fuzzy systems in medicine [4][6].

7. Conclusion
An overview of the fuzzy logic based control and its applications are presented in this paper. The paper presents the basic principles of the fuzzy logic and its difference to the conventional logic theory. The basic terms of fuzzy logic, i.e. fuzzy sets, fuzzy set operations; fuzzy rules are described with the help of suitable examples. A brief overview of the complete fuzzy control decision making is presented. The paper also presents brief overview of the applications of fuzzy logic in various fields.

8. References
