Introduction to Fuzzy Control*

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Abstract

In the last few years the applications of artificial intelligence techniques have been used to convert human experience into a form understandable by computers. Advanced control based on artificial intelligence techniques is called intelligent control. Intelligent systems are usually described by analogies with biological systems by, for example, looking at how human beings perform control tasks, recognize patterns, or make decisions. There exists a mismatch between humans and machines: humans reason in uncertain, imprecise, fuzzy ways while machines and the computers that run them are based on binary reasoning. Fuzzy logic is a way to make machines more intelligent enabling them to reason in a fuzzy manner like humans. Fuzzy logic, proposed by Lotfy Zadeh in 1965, emerged as a tool to deal with uncertain, imprecise, or qualitative decision-making problems. Controllers that combine intelligent and conventional techniques are commonly used in the intelligent control of complex dynamic systems. Therefore, embedded fuzzy controllers automate what has traditionally been a human control activity.

1 Introduction

Traditional control approach requires modeling of the physical reality. Three methods may be used in the description of a system [2] [3]:

1.1 Experimental Method: By experimenting and determining how the process reacts to various inputs one can characterize an input-output table. Graphically the method is equivalent to plotting some discrete points of the input-output curve, using the horizontal axis for input and the vertical axis for output. By understanding such input-output reaction, one can design a controller. The disadvantages are several: the process equipment may not be available for experimentation, the procedure would usually be very costly, and for a large number of input values it is impractical to measure the output and interpolation between measured outputs would be required. One must also be careful to determine the expected ranges of inputs and outputs to make sure that they fall within the range of the measuring instruments available.

1.2 Mathematical Modeling: Control engineering requires an idealized mathematical model of the controlled process, usually in the form of differential or difference equations. Laplace transforms and z-transforms are respectively used. In order to make mathematical models simple enough, certain assumptions are made, one of which is that the process is linear, that is, its output is proportional to the input. Linear techniques are valuable because they provide good insight. Besides, there exists no general theory for the analytic solution of nonlinear differential equations and consequently no comprehensive analysis tools for nonlinear dynamic systems. Another assumption is that the process parameters do not change in time (that is, the system is time-invariant) despite system component deterioration and environmental changes. The following problems arise in developing a meaningful and

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realistic mathematical description of an industrial process: (1) Poorly understood phenomena, (2) Inaccurate values of various parameters, (3) Model complexity.

1.3 Heuristics Method: The heuristic method consists of modeling and understanding in accordance with previous experience, rules-of-thumb and often-used strategies. A heuristic rule is a logical implication of the form: **If** <condition> **Then** <consequence>, or in a typical control situation: **If** <condition> **Then** <action>. Rules associate conclusions with conditions. Therefore, the heuristic method is actually similar to the experimental method of constructing a table of inputs and corresponding output values where instead of having crisp numeric values of input and output variables, one use fuzzy values: IF input_voltage = *Large* THEN output_voltage = *Medium*. The advantages of the heuristic method are: (1) It is not required the assumption of linearity and, (2) heuristic rules can be integrated to the control strategies of human operators.

Fuzzy control strategies come from experience and experiments rather than from mathematical models and, therefore, linguistic implementations are much faster accomplished. Fuzzy control strategies involve a large number of inputs, most of which are relevant only for some special conditions. Such inputs are activated only when the related condition prevails. In this way, little additional computational overhead is required for adding extra rules. As a result, the rule base structure remains understandable, leading to efficient coding and system documentation.

2 Logical Inference

A connection between cause and effect, or a condition and a consequence is made by reasoning. Reasoning can be expressed by a logical inference, or by the evaluation of inputs in order to draw a conclusion. We usually follow rules of inference which have the form: IF cause1 = A and cause2 = B THEN effect = C. Where A, B and C are linguistic variables. For example, IF "room temperature" is *Medium* THEN "set fan speed to *Fast*" *Medium* is a function defining degrees of room temperature while *Fast* is a function defining degrees of speed. The intelligence lies in associating those two terms by means of an inference expressed in heuristic IF…THEN terms. In order to convert a linguistic term into a computational framework one needs to use the fundamentals of set theory. On the statement IF "room temperature" is *Medium*, we have to ask the following question "Is the room temperature *Medium*" ? A traditional logic, also called Boolean logic, would have two answers: YES and NO. Therefore, the idea of membership of an element x in a set A is a function $\mu_A(x)$ whose value indicates if that element belongs to the set A. Boolean logic would indicate, for example: $\mu_A(x) = 1$, then the element belongs to set A, or $\mu_A(x) = 0$, the element does not belong to set A.

3 Fuzzy Sets

A fuzzy set is represented by a membership function defined on the universe of discourse. The universe of discourse is the space where the fuzzy variables are defined. The membership function gives the grade, or degree, of membership within the set, of any element of the universe of discourse. The membership function maps the elements of the universe onto numerical values in the interval [0, 1]. A membership function value of zero implies that the corresponding element is definitely not an element of the fuzzy set, while a value of unity means that the element fully belongs to the set. A grade of membership in between corresponds to the fuzzy membership to set. In crisp set theory, if someone is taller than 1.8 meters, we can state that such person belongs to the "set of tall people". However, such sharp change from 1.7999 meters of a "short person" to 1.8001 meters of a "tall person" is against the common sense. Another example could be given as follows: Suppose a highway has a speed limit as 65 miles/hour. Those who drive faster than 65 miles/hours belongs to the set A whose elements are violators and their membership function has the value of 1. On the other hand, those who drive slower do not belong to the set A. The sharp transition between membership and non-membership would be realistic? Should there be a traffic summons issued to drivers who are caught at 65.5 miles/hour ? Or at 65.9 miles/hour ? Therefore, in practical situations there is always a natural fuzzification when someone analysis statements and a smooth membership curve usually better describes the grade that an element belongs to a set.

3.1 Fuzzification

Fuzzification is the process of decomposing a system input and/or output into one or more fuzzy sets. Many types of curves can be used, but triangular or trapezoidal shaped membership functions are the most common because they are easier to represent in embedded controllers. Fig 1 shows a system of fuzzy sets for an input with trapezoidal and triangular membership functions. Each fuzzy set spans a region of input (or output) value graphed with the membership. Any particular input is interpreted from this fuzzy set and a degree of membership is interpreted. The membership functions should overlap to allow smooth mapping of the system. The process of fuzzification allows the system inputs and outputs to be expressed in linguistic terms so that rules can be applied in a simple manner to express a complex system.

Suppose a simplified implementation for an air-conditioning system with a temperature sensor. The temperature might be acquired by a microprocessor which has a fuzzy algorithm to process an output to continuously control the speed of a motor which keeps the room in a "good temperature," it also can direct a vent upward or downward as necessary. The figure illustrates the process of fuzzification of the air temperature. There are five fuzzy sets for temperature: COLD, COOL, GOOD, WARM, and HOT.

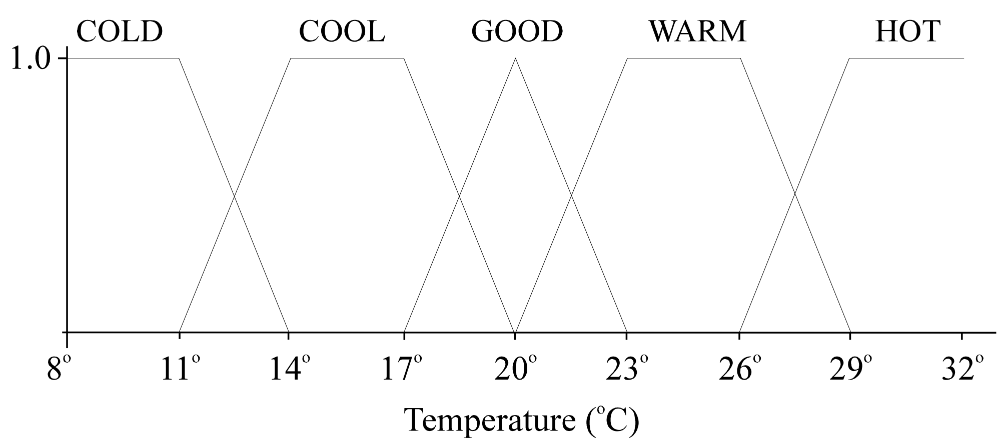

Fig. 1 Fuzzy sets defining temperature

The membership function for fuzzy sets COOL and WARM are trapezoidal, the membership function for GOOD is triangular, and the membership functions for COLD and HOT are half-triangular with shoulders indicating the physical limits for such process (staying in a place with a room temperature lower than 8 degrees Celsius or above 32 degrees Celsius would be quite uncomfortable). The way to design such fuzzy sets is a matter of degree and depends solely on the designer's experience and intuition. Most probably an Eskimo and an Equatorian would draw very different membership functions for such fuzzy sets! The figure shows some non-overlaping fuzzy sets, which can indicate any non-linearity in the modeling process. There an input temperature of 18 degrees Celsius would be considered COOL with a degree of 0.75 and would be considered GOOD with a degree of 0.25. In order to build the rules that will control the air conditioning motor, we could watch how a human expert would adjust the settings to speed up and slow down the motor in accordance to the temperature, obtaining the rules empirically. If the room temperature is good, keep the motor speed medium, if it is warm, turn the knob of the speed to fast, and blast the speed, if the room is hot. On the other hand, if the temperature is cool, slow down the speed, and stop the motor if it is cold. This is the beauty of fuzzy logic: to turn common-sense, linguistic descriptions, into a computer controlled system. Therefore, it is required to understand how to use some logical operations to build the rules.

Boolean logic operations must be extended in fuzzy logic to manage the notion of partial truth - truth values between “completely true” and “completely false.” A fuzziness nature of a statement like “X is LOW” might be combined to the fuzziness statement of “Y is HIGH” and a typical logical operation could be given as X is LOW and Y is HIGH. What is the truth value of this and operation? The logic operations with fuzzy sets are performed with the membership functions. Although there various other interpretations for fuzzy logic operations, the following definitions are very convenient in embedded control applications:

truth(X and Y) = Min(truth(X), truth(Y))

truth(X or Y) = Max(truth(X), truth(Y))

truth(not X) = 1.0 - truth(X)

3.2 Defuzzification

After fuzzy reasoning we have a linguistic output variable which needs to be translated into a crisp value. The objective is to derive a single crisp numeric value that best represents the inferred fuzzy values of the linguistic output variable. Defuzzification is such inverse transformation which maps the output from the fuzzy domain back into the crisp domain. Some defuzzification methods tend to produce an integral output considering all the elements of the resulting fuzzy set with the corresponding weights. Other methods take into account just the elements corresponding to the maximum points of the resulting membership functions. The following defuzzification methods are of practical importance [2] [3]:

Center-of-Area (C-o-A) - The C-o-A method is often referred to as the Center-of-Gravity method because it computes the centroid of the composite area representing the output fuzzy term.

Center-of-Maximum (C-o-M) - In the C-o-M method only the peaks of the membership functions are used. The defuzzified crisp compromise value is determined by finding the place where the weights are balanced. Thus the areas of the membership functions play no role and only the maxima (singleton memberships) are used. The crisp output is computed as a weighted mean of the term membership maxima, weighted by the inference results.

Mean-of-Maximum (M-o-M) – The M-o-M is used only in some cases where the C-o-M approach does not work. This occurs whenever the maxima of the membership functions are not unique and the question is as to which one of the equal choices one should take.

4 Fuzzy Controllers

Most commercial fuzzy products are rule-based systems that receive current information in the feedback loop from the device as it operates and control the operation of a mechanical or other device [4] [5]. A fuzzy logic system has four blocks as shown in Fig. 2. Crisp input information from the device is converted into fuzzy values for each input fuzzy set with the fuzzification block. The universe of discourse of the input variables determines the required scaling for correct per-unit operation. The scaling is very important because the fuzzy system can be retrofitted with other devices or ranges of operation by just changing the scaling of the input and output. The decision-making-logic determines how the fuzzy logic operations are performed (Sup-Min inference), and together with the knowledge base determine the outputs of each fuzzy IF-THEN rules. Those are combined and converted to crispy values with the defuzzification block. The output crisp value can be calculated by the center of gravity or the weighted average.

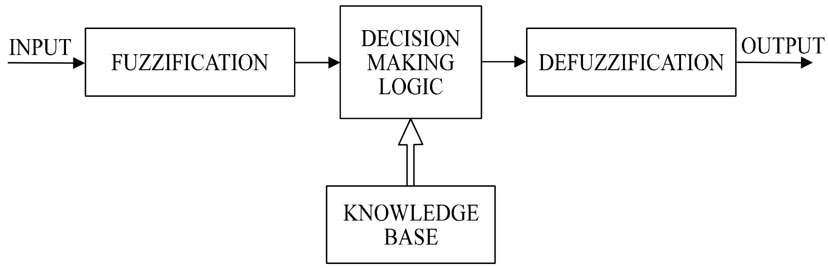

Fig. 2 Fuzzy Controller Block Diagram

In order to process the input to get the output reasoning there are six steps involved in the creation of a rule based fuzzy system:

1. Identify the inputs and their ranges and name them.
2. Identify the outputs and their ranges and name them.
3. Create the degree of fuzzy membership function for each input and output.
4. Construct the rule base that the system will operate under
5. Decide how the action will be executed by assigning strengths to the rules
6. Combine the rules and defuzzify the output

5 Conclusion

Fuzzy systems are indicating good promise in consumer products, industrial and commercial systems, and decision support systems. The term "fuzzy" refers to the ability of dealing with imprecise or vague inputs. Instead of using complex mathematical equations, fuzzy logic uses linguistic descriptions to define the relationship between the input information and the output action. In engineering systems, fuzzy logic provides a convenient and user-friendly front-end to develop control programs, helping designers to concentrate on the functional objectives, not on the mathematics. This introductory text discussed the nature of fuzziness and showed how fuzzy operations are performed, and how fuzzy rules can incorporate the underlying knowledge. Fuzzy logic is a very powerful tool that is pervading every field and signing successful implementations.

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