فصل هشتم

کنترل فازی و
سیستم های خبره فازی

FUZZY CONTROL AND
FUZZY EXPERT SYSTEMS

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Outline

- Introducing the fuzzy logic controller (FLC)
- The architecture of the FLC
- Study the components step by step and suggest a design procedure of the FLC.
- An example of the design procedure is also given.
- The structure and function of the fuzzy expert systems are similar to those of the FLC, and thus the design procedure of FLC can be used in the fuzzy expert systems.

Fuzzy Logic Controller (FLC)

Advantage of Fuzzy Logic Controller

- Fuzzy logic is much closer in spirit to human thinking and natural language than the traditional (classical) logical systems.
- Basically, it provides an effective means of capturing the approximate, inexact nature of the real world. Therefore, the essential part of the fuzzy logic controller (FLC) is a set of linguistic control strategy based on expert knowledge into an automatic control strategy.
- The FLC is considered as a good methodology because it yields results superior to those obtained by conventional control algorithms.

Fuzzy Sets. Chapter 6- Fuzzy Logic shavandi@sharif.edu

Fuzzy Logic Controller (FLC)

Advantage of Fuzzy Logic Controller

- In particular the FLC is useful in two cases:
- (1) The control processes are too complex to analyze by conventional quantitative techniques.
- (2) The available sources of information are interpreted qualitatively, inexactly, or uncertainly.

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Configuration of Fuzzy Logic Controller

- There is no systematic procedure for the design of an FLC.
- However we can present here a basic configuration of FLC as shown in (Fig 10.1.).
- The configuration consists of four main components:
  - Fuzzification interface,
  - knowledge base,
  - decision-making logic,
  - defuzzification interface.

Configuration of Fuzzy Logic Controller

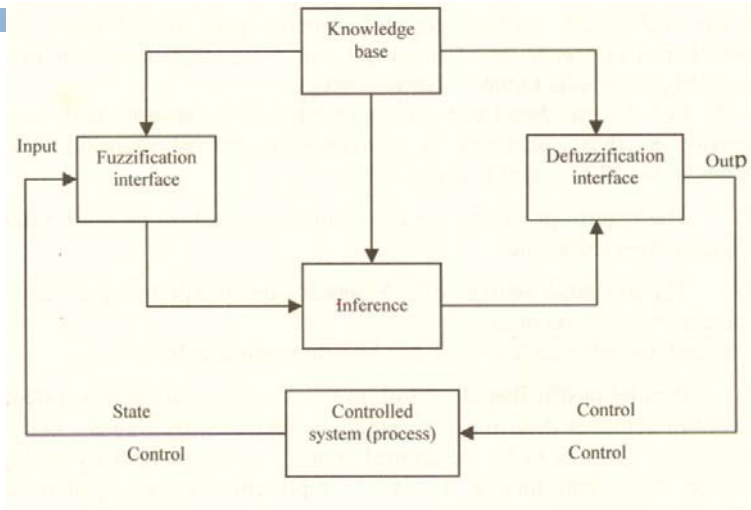


Fig. 10.1. Configuration of FLC

Configuration of Fuzzy Logic Controller

The fuzzification interface

- The fuzzification interface transforms input crisp values into fuzzy values and it involves the following functions:
- Receives the input values
- Transforms the range of values of input variable into corresponding universe of discourse
- Converts input data into suitable linguistic values (fuzzy sets).
- This component is necessary when input data are fuzzy sets in the fuzzy inference.

Configuration of Fuzzy Logic Controller

Knowledge Base

- It consists of a data base and a linguistic rule base.
- The data base contains necessary definitions which are used in control rules and data manipulation.
- The linguistic rule base defines the control strategy and goals by means of linguistic control rules.

Configuration of Fuzzy Logic Controller

Decision Making Logic

- The decision-making logic performs the following functions:
- Simulates the human decision-making procedure based on fuzzy concepts
- Infers fuzzy control actions employing fuzzy implication and linguistic rules.

Configuration of Fuzzy Logic Controller

Defuzzification interface

- A scale mapping which converts the range of output values into corresponding universe of discourse
- Defuzzification which yields a non-fuzzy control action from an inferred fuzzy control action.

Choice of State Variables and Control Variables

- Before starting the detailed procedure of the FLC design, we have to choose the variables.
- A fuzzy control system is designed to control a process, and thus it is needed to determine state variables and control variables of the process.
- The state variables become input variables of the fuzzy control system,
- The control variables become output variables.
- Selection of the variables depends on expert knowledge on the process.
- In particular, variables such as state, state error, state error deviation, and state error integral are often used.

Fuzzification Interface Component

- In the fuzzification component, there are the following main issues to be considered:
  - scale mapping of input data,
  - and selection of fuzzification functions.

- **Scale mapping of input data:**

  We have to decide a strategy to convert the range of values of input variables into corresponding universe of discourse.

  Example: Normalize the data between -1 and 1.

Fuzzification Interface Component

Selection of fuzzification function:

A fuzzification operator has the effect of transforming crisp data into fuzzy sets.

$$x = fuzzifier\ (x_o)$$

Where *Xo is a observed crisp value and x is a fuzzy set, and fuzzifier* represents a fuzzification operator.

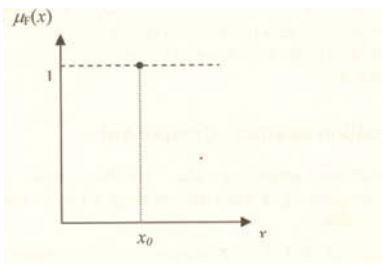


Fig. 10.2. Fuzzification function for fuzzy singleton

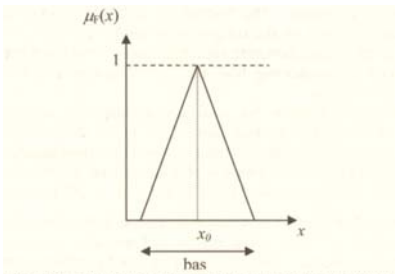


Fig. 10.3. Fuzzification function for fuzzy triangular number

Knowledge Base Component: Data Base

In the data base part, there are four principal design parameters for an FLC:

- Discretization and Normalization of universe of discourse,
- Fuzzy partition of input and output spaces,
- and membership function of primary fuzzy set.

- **Discretization and Normalization of universe of discourse**
  - A universe of discourse in an FLC is either discrete or continuous.
  - If the universe is continuous, a discrete universe may be formed by a discretization procedure.
  - A data set may be also normalized into a certain range of data.

Knowledge Base Component: Data Base

Discretization

- It is often referred to as quantization.
- The quantization discretizes a universe into a certain number of segments.
- Each segment is labeled as a generic element and forms a discrete universe
- A fuzzy set is then defined on the discrete universe of discourse.
- The number of quantization level affects on adequate approximation, control performance, and memory storage.
- The mapping can be uniform (linear), non-uniform (non linear), or both.

Knowledge Base Component: Data Base

Discretization

- (Table 10.1) shows an example of discretization, where a universe of discourse is discretized into 13 levels (-6, -5, -4, ... , 0, 1, ... , 5, 6).

Table 10.1 An example of discretization

Range	Level No.
$x \le -2.4$	-6
$-2.4 < x \le -2.0$	-5
$-1.6 < x \le -0.8$	-4
$-0.8 < x \le -0.4$	-3
$-0.4 < x \le -0.2$	-2
$-0.2 < x \le -0.1$	-1
$-0.1 < x \le +0.1$	0
$+0.1 < x \le +0.2$	1
$+0.2 < x \le +0.4$	2
$+0.4 < x \le +0.8$	3
$+0.8 < x \le +1.1$	4
$+1.1 < x \le +1.4$	5
$+1.4 < x$	6

Knowledge Base Component: Data Base

Normalization

- The scale mapping can be uniform, non-uniform, or both.
- (Table 10.2) shows an example, where the universe of discourse [-6.9, +4.5] is transformed into the normalized closed interval [-1, 1].

Table 10.2. An example of normalization

Range	Normalized segments	Normalized universe
[−6.9, −4.1]	[−1.0, −0.5]	
[−4.1, −2.2]	[−0.5, −0.3]	
[−2.2, −0.0]	[−0.3, 0.0]	[−1.0, +1.0]
[−0.0, +1.0]	[0.0, +0.2]	
[+1.0, +2.5]	[+0.2, +0.6]	
[+2.5, +4.5]	[+0.6, +1.0]	

Knowledge Base Component: Fuzzy partition of input and output spaces

- A fuzzy partition of the space determines how many terms should exist in a term set.
- This is the same problem to find the number of primary fuzzy sets (linguistic terms).
- There are seven linguistic terms often used in the fuzzy inference:

NB: negative big

NM: negative medium

NS: negative small

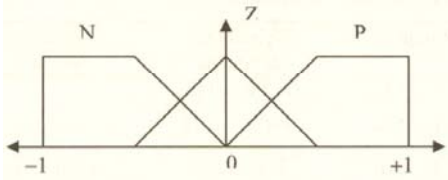
ZE: zero

PS: positive small

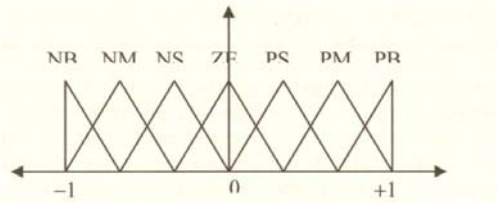
PM: positive medium

PB: positive big

Knowledge Base Component: Fuzzy partition of input and output spaces



(a) N: negative, Z: zero, P: positive



(b) NB, NM, NS, ZE, PS, PM, PB

Fig. 10.3. Example of fuzzy partition with linguistic terms

Knowledge Base Component: Fuzzy partition of input and output spaces

- The number of fuzzy terms in an input space determines the maximum number of fuzzy control rules.
- Suppose a fuzzy control system with two input and one output variables.
- If the input variables have 5 and 4 terms, the maximum number of control rules that we can construct is 20 (5 x 4) as shown in (Fig *10.4.*). *(Fig 10.5) shows an example of system having 3* fuzzy rules.

Knowledge Base Component: Fuzzy partition of input and output spaces

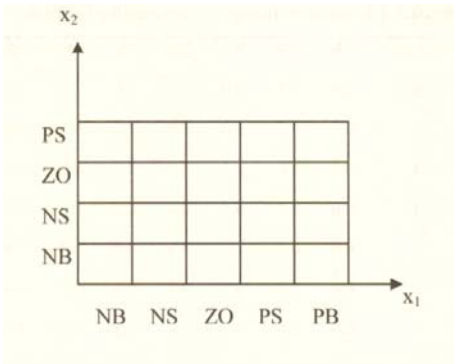


Fig. 10.4. A fuzzy partition in 2-dimension input space

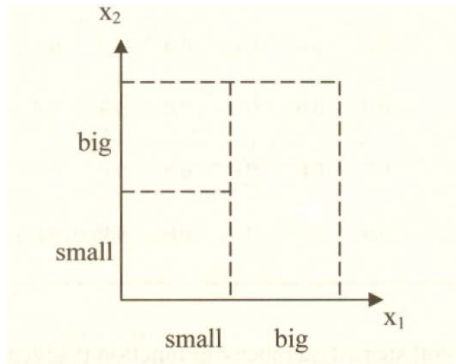


Fig. 10.5. A fuzzy partition having three rules

Knowledge Base Component: Membership function of primary fuzzy set

- There are various types of membership functions such as triangular, trapezoid, and bell shapes.
- (Table 10.3) shows an example defining triangular membership functions on the discretized universe of discourse in (Table 10.1.)
- For example, term NM is defined such as:

$$\mu_{NM}(-6) = 0.3$$
$$\mu_{NM}(-5) = 0.7$$
$$\mu_{NM}(-4) = 1.0$$
$$\mu_{NM}(-3) = 0.7$$
$$\mu_{NM}(-2) = 0.3$$

Knowledge Base Component: Membership function of primary fuzzy set

Table 10.3. Definition of triangular membership function

Level No.	NB	NM	NS	ZE	PS	PM	PB
−6	1.0	0.3	0.0	0.0	0.0	0.0	0.0
−5	0.7	0.7	0.0	0.0	0.0	0.0	0.0
−4	0.3	1.0	0.3	0.0	0.0	0.0	0.0
−3	0.0	0.7	0.7	0.0	0.0	0.0	0.0
−2	0.0	0.3	1.0	0.3	0.0	0.0	0.0
−1	0.0	0.0	0.7	0.7	0.0	0.0	0.0
0	0.0	0.0	0.3	1.0	0.3	0.0	0.0
1	0.0	0.0	0.0	0.7	0.7	0.0	0.0
2	0.0	0.0	0.0	0.3	1.0	0.3	0.0
3	0.0	0.0	0.0	0.0	0.7	0.7	0.0
4	0.0	0.0	0.0	0.0	0.3	1.0	0.3
5	0.0	0.0	0.0	0.0	0.0	0.7	0.7
6	0.0	0.0	0.0	0.0	0.0	0.3	1.0

Knowledge Base Component: Membership function of primary fuzzy set

- An example of bell shaped membership function is given in (Table *10.4)* and (Fig 10.6)

Table 10.4. Definition of bell-shaped membership function

Normalized universe	Normalized segments	m_f	σ_f	Fuzzy sets
	[−1.0, −0.5]	−1.0	0.4	NB
	[−0.5, −0.3]	−0.5	0.2	NM
	[−0.3, −0.0]	−0.2	0.2	NM
[−1.0, +1.0]	[−0.0, +0.2]	0.0	0.2	ZE
	[+0.2, +0.6]	0.2	0.2	PS
	[+0.6, +0.8]	0.5	0.2	PM
	[+0.8, +1.0]	1.0	0.4	PB

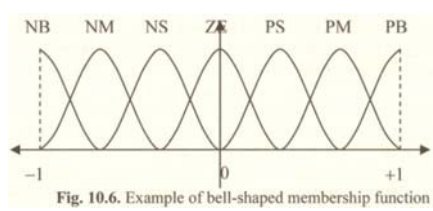


Fig. 10.6. Example of bell-shaped membership function

$$\mu_f(x) = \exp\{\frac{-(x-m_f)^2}{2\sigma_f^2}\}$$

Rule Base: Fuzzy Control Rules

- State variables are in the antecedent part of rules and control variables are in the consequent part. In the case of MISO (multiple input single output), they are characterized as a collection of rules of the form.

R_1: if x is A_1, … and y is B_1 then z is C_1
R_2: if x is A_2, … and y is B_2 then z is C_2
…
R_n: if x is A_n, … and y is B_n then z is C_n

where x, … y and z are linguistic variables representing the process state variable and the control variable. A_i, … B_i and C_i are linguistic values of the variables x, … y and z in the universe of discourse U, … V and W, respectively i = 1, 2, … , n.

Rule Base: Fuzzy Control Rules

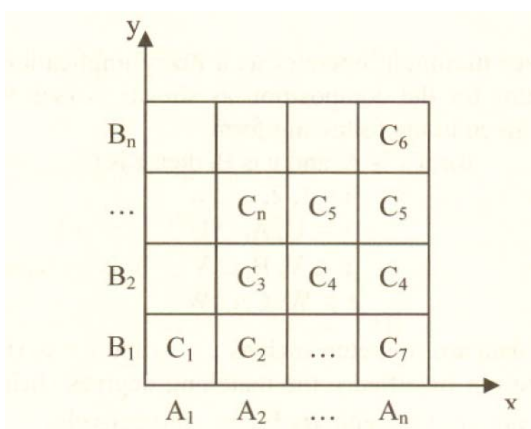


Fig 10.7. Fuzzy rules represented by a rule table

Inference (Decision Making Logic)

In general, in decision making logic part, we use three inference methods described in the previous chapter:

- Mamdani method
- Larsen method
- TSK method.

Defuzzification

- In many practical applications, a control command is given as a crisp value. Therefore it is needed to defuzzify the result of the fuzzy inference.
- A defuzzification is a process to get a non-fuzzy control action that best represents the possibility distribution of an inferred fuzzy control action.
- Use one of the defuzzification methods to defuzzification.

Design Procedure of Fuzzy Logic Controller

- When we decided to design a fuzzy logic controller, we can follow the following design procedure:
  1. Determination of state variables and control variables
  2. Determination of inference method
  3. Determination of fuzzification method
  4. Discretization and normalization of state variable space
  5. Partition of variable space
  6. Determination of the shapes of fuzzy sets
  7. Construction of fuzzy rule base
  8. Determination of defuzzification strategy
  9. Test and tuning

Fuzzy Expert Systems

- An expert system is a program which contains human expert's knowledge and gives answers to the user's query by using an inference method.
- The knowledge is often stored in the form of rule base, and the most popular form is that of "if-then".
- A fuzzy expert system is an expert system which can deal uncertain and fuzzy information.
- In our real world, a human expert has his knowledge in the form of linguistic terms. Therefore it is natural to represent the knowledge by fuzzy rules and thus to use fuzzy inference methods.

Fuzzy Expert Systems

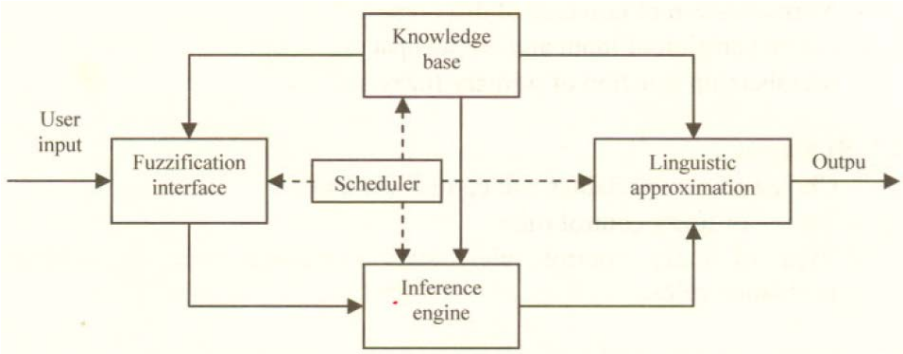


Fig. 10.16. Configuration of fuzzy expert system

Fuzzy Expert Systems: Fuzzification Interface

- The fuzzification strategy, if necessary, is similar to that of the fuzzy logic controller.

Fuzzy Expert Systems: Linguistic Approximation

- As we stated before, a fuzzy expert system does not control a machine nor a process, and thus, in general, the defuzzification is not necessary.
- Instead of the defuzzification module, sometimes we need a linguistic approximation module.
- This module finds a linguistic term which is closest to the obtained fuzzy set.
- To do it, we may use a measuring technique of distance between fuzzy sets.

Fuzzy Expert Systems: Scheduler

- This module controls all the processes in the fuzzy expert system.
- It determines the rules to be executed and sequence of their executions.
- It may also provide an explanation function for the result. For example, it can show the reason how the result was obtained.