FUZZY CONTROL:

In normal control systems, decisions are made using strict rules. For example, if the distance is 5 m or less, the system applies the brakes. But this method is not very flexible. To improve it, we can add more rules, such as applying 90% brakes at 6 m and 100% brakes at 5 m. This gives slightly better control, but it still has problems. We would need many rules to cover every possible distance value, which makes the system complicated. Also, this method cannot understand everyday words like “near,” “far,” “clean,” or “dirty.” To solve this problem, fuzzy control is used. Fuzzy control allows the system to work with approximate or human-like descriptions. It uses fuzzy sets and fuzzification to interpret inputs, fuzzy rules to make decisions, and defuzzification to convert the result into a clear output.

CRISP VS FUZZY:

In control systems and decision-making processes, information can be represented in two main ways: crisp values and fuzzy values. Crisp values follow classical logic, where variables have clear and exact values. In contrast, fuzzy values follow fuzzy logic, which allows partial or approximate values similar to human thinking. This concept is widely used in modern control systems, robotics, and biomedical engineering applications to handle uncertainty and imprecise information.

- **Crisp Values:**

Crisp values represent information in a precise and definite manner. In classical logic, a statement can only be either **true (1)** or **false (0)**. There is no intermediate value between these two states. For example, in a temperature control system, if the temperature is **above 30°C**, the fan turns on; if it is **below 30°C**, the fan turns off. This system works well when the boundaries are clearly defined. Crisp systems are commonly used in traditional digital electronics, computer programming, and conventional control systems. However, they cannot easily handle situations where values change gradually or when decisions need to consider uncertainty.

Characteristics:

Crisp values have several important characteristics. First, they are precise and exact, meaning each variable has a fixed numerical value. Second, crisp logic uses binary decision making, where the output is either completely true or completely false. Third, crisp systems rely on strict boundaries or thresholds. For instance, if a distance is less than 5 meters, brakes are applied; otherwise, no action is taken. Because of these rigid boundaries, crisp systems may not behave smoothly when the input value changes slightly around the threshold.

Limitations:

Although crisp logic is simple and easy to implement, it has several limitations. Real-world situations often involve uncertainty and gradual changes, which cannot be handled effectively by strict binary rules. For example, words such as “warm,” “very hot,” or “slightly dirty” cannot be represented accurately using crisp values. This limitation makes crisp logic unsuitable for many real-world applications such as intelligent control systems, medical diagnosis, and robotics.

- **Fuzzy Values:**

Fuzzy values are used to represent uncertain or approximate information. Instead of assigning only 0 or 1, fuzzy logic allows values between 0 and 1, representing different degrees of truth. For example, a temperature of 28°C may be considered 0.6 "warm" and 0.4 "hot." This allows systems to make more flexible decisions similar to human reasoning. Fuzzy logic is particularly useful in systems where inputs are not strictly defined and where human-like interpretation is required.

Characteristics:
Fuzzy values have unique characteristics that make them suitable for complex systems. First, they allow partial membership, meaning an element can belong to multiple categories at the same time. Second, fuzzy logic supports gradual transitions rather than abrupt changes. Third, fuzzy systems use linguistic variables, such as low, medium, and high, instead of strict numerical limits. These features help fuzzy systems deal with imprecise data more effectively.

Applications:

Fuzzy values are widely used in modern technology. They are applied in robot control systems, smart washing machines, air-conditioning systems, automotive braking systems, and medical decision-making systems. In robotics, fuzzy logic helps robots respond smoothly to changing environments. In medicine, fuzzy systems can assist doctors in diagnosing diseases by handling uncertain patient symptoms.

The main difference between crisp and fuzzy values lies in the way they represent information. Crisp values are exact and binary, while fuzzy values are approximate and continuous. Crisp systems use strict rules and boundaries, whereas fuzzy systems allow flexible decision making based on degrees of truth. Crisp logic is simple and suitable for well-defined problems, but fuzzy logic is more effective in handling real-world situations with uncertainty. Crisp values and fuzzy values represent two different approaches to handling information in control systems. Crisp values provide precise and clear decisions, but they lack flexibility when dealing with uncertain or vague data. Fuzzy values, on the other hand, allow gradual reasoning and human-like interpretation of inputs. Because of these advantages, fuzzy logic has become an important tool in robotics, biomedical engineering, and intelligent control systems.

FUZZY SETS: DEGREES OF TRUTH AND MEMBERSHIP:

A fuzzy set is used to describe things that are not exactly true or false, but partly true. In a fuzzy set, every value has a degree of membership, which shows how much it belongs to that set. This value ranges from 0 to 1. A value of 1 (or 100%) means it completely belongs to the set, while 0 means it does not belong at all. Values between 0 and 1 represent partial truth. This idea is part of Fuzzy Logic, which was introduced by Lotfi Zadeh.

To understand this easily, consider a washing machine example. Suppose there is a rule:
IF water is clean THEN washing time=0.

In a crisp system, the water must be perfectly clean for the rule to be true. If there is even a small amount of dirt, the system will say the water is not clean. This means crisp logic allows no small variations.

But in a fuzzy system, the water does not have to be perfectly clean. Instead, it can be partially clean. For example, completely clean water may have 100% membership (1) in the CLEAN_WATER set. Water with a small amount of dirt may still be 95% clean, and water with more dirt may be 90% clean. This means the water can still belong to the CLEAN_WATER set, but with a lower degree of membership.

At the same time, we can also define another fuzzy set called DIRTY_WATER. Pure clean water will have 0 membership in the DIRTY_WATER set. Dirty water may have 100% membership in the DIRTY_WATER set. A water sample can even belong to both sets at the same time with different membership values. For example, a water sample that is 90% clean might also be 15% dirty.

In a normal crisp rule, the rule works only when the condition is completely true. For example:
IF rule is true THEN perform the action.
But in a fuzzy rule, the condition does not have to be completely true. Instead, it works based on how true the condition is (its degree of membership). The system uses this value to calculate the final output.

For example, a fuzzy control system may use two inputs (INPUT1 and INPUT2) to control an output (OUTPUT). The rule may look like this:
IF INPUT1 belongs to a set with some membership value AND INPUT2 belongs to another set with some membership value, THEN OUTPUT is produced with a certain membership value.

Thus, fuzzy sets allow systems to handle uncertainty and gradual changes, just like humans do when they say something is "slightly dirty," "mostly clean," or "very hot." In fuzzy control systems, this process is followed by fuzzification (converting inputs into fuzzy values), applying fuzzy rules, and defuzzification (converting the result into a final output).

FUZZIFICATION:

Fuzzification is the process of converting input and output values into their membership functions. The result of fuzzification is a set of graphs or equations that describe the degree of membership of different values in different fuzzy sets. To fuzzify a variable, its range of possible values is divided into a number of sets, each describing a particular portion of the range. Subsequently, each range is represented by an equation or a graph that describes the degree of truth or membership of each value within the range. The number of sets, the range that each set represents, and the type of representation is arbitrary and a choice of the designer. As we see later, this cane modified and improved when the system is simulated and analyzed.

A number of possible representations are available for each set. If you create your own fuzzy system, you May use any representation you find appropriate. However, when you use a commercial system, you may be

limited to what is available. The following membership functions are common:

Gaussian membership function: This is a natural way to represent a distribution. Generally, more mathematical operations are needed to use the Gaussian distribution, the Gaussian representation may be modified into simpler forms for easier application.

Trapezoidal membership function: The common trapezoidal membership function used to represent a Gaussian function in a simpler way. Here, the membership function is represented by three simple lines, requiring only four points. Each section is a straight line, and therefore the degree of membership for each value of the variable can easily be calculated from the line equations.

Triangular membership function: This is also a very common membership function that simplifies a Gaussian function, requiring only three points. As shown in Figure 12.3, each section is a straight line. Degrees of membership for each value of the variable are simply calculated from the line equations.

Z-shaped and S-shaped membership functions: These second-order functions may be used to represent the upper and lower limits of a variable, where the degrees of membership may remain the same (0 or 1) for a range of values. A trapezoidal membership function with a vertical left or right side may be used as a simple model for S- and Z-shaped functions.

FUZZY INFERENCE RULES:

Fuzzy inference rules are the controller part of the system consisting of a collection of rules related to the fuzzy sets, the input variables, and the output variables and are meant to allow the system to decide what to do in each case. Fuzzy inference is the process of mapping input values to output values using fuzzy logic. It is the core part of a fuzzy logic system, where decisions are made based on a set of **IF–THEN rules**. These rules imitate human reasoning and help in handling uncertain or imprecise information. The rules usually take one of the following forms, depending on the number of input and output variables:

if < condition > then < consequence>

if < condition1 and (or) condition2 > then < consequence>

if < condition1 and (or) condition2 > then < consequence1 and (or) consequence2>

As an example, for a system where the speed is one input variable, load is the second input variable, and the motor power is the output variable, a fuzzy rule may be:

IF speed is FAST **and** load is MEDIUM then power is HIGH

or IF speed is FAST **or** load is MEDIUM then power is HIGH

Obviously, these two rules will behave differently. Based on commonly used truth tables, in the first case, both conditions must be true for the consequence, while in the second case, either condition results in a consequence. However, remembering that these are all rather fuzzy – not crisp – values, they do not result in true or false consequences. Therefore, to evaluate the “and” and the “or” rules, we use the following:

The result of an “and” operation is the minimum of the two values.

The result of an “or” operation is the maximum of the two values.

Each fuzzy rule has two main parts:

- **Antecedent(IFpart):**
  Contains input conditions combined using logical operators like AND/OR. Example: *temperature is high AND humidity is low*
- **Consequent (THENpart):**

  Specifies the output action.

  Example: fan speed is fast

Defuzzification: The process of converting a fuzzy output into a single clear (crisp) value that can be used in real applications. After evaluating the fuzzy rules, the system produces results as degrees of membership in different output sets instead of one exact value. For example, a motor’s power may be described as 25% LOW and 75% MEDIUM. Defuzzification combines these fuzzy results and converts them into one specific numerical value, which can then be given to the motor controller for actual operation. A number of different possibilities exist for defuzzification. We will consider two common and useful techniques: center of gravity, and Mamdani inference method.

Center of Gravity (COG) is a common defuzzification method used to convert a fuzzy output into a single crisp value. It works by finding the “balance point” or average of the area under the output membership function curve. In simple terms, it considers all possible output values and their degrees of membership, and calculates a single value that represents the overall result.

The **Mamdani inference method** is one of the most widely used fuzzy inference techniques. It uses IF–THEN rules with fuzzy inputs and produces a fuzzy output. The method evaluates each rule, combines the results, and then applies a defuzzification method (usually Center of Gravity) to get a final crisp output. It is popular because it is simple, intuitive, and closely resembles human decision-making.

Example

Consider a temperature control system:

- Rule 1: IF temperature is low THEN heater is high

- Rule 2: IF temperature is medium THEN heater is moderate
- Rule 3: IF temperature is high THEN heater is low

Based on input temperature, the system evaluates all rules and produces a suitable output.

Advantages

- Handles uncertainty and imprecision
- Mimics human decision-making
- Easy to design and understand
- Suitable for complex systems without exact mathematical models

Applications

- Industrial control systems
- Washing machines and air conditioners
- Medical diagnosis
- Robotics and automation

SIMULATION:

In fuzzy systems, the choices we make for membership functions, variable ranges, and rules may not always give the best results, so it is important to test and improve the system through simulation. Tools like MATLAB’s Fuzzy Logic Toolbox are used to run the fuzzy system, check outputs for different inputs, and visualize the results using graphs (often 3D surfaces). These graphs help us understand whether the rules and membership functions are working properly or need modification. If the output is not satisfactory, the designer adjusts the rules or fuzzy sets until better results are obtained. Once finalized, the system is implemented in a microprocessor for real-time operation. Sometimes, the output graph may have flat regions where output does not change even if inputs vary; this is acceptable in systems like gear transmissions with fixed levels. However, in systems requiring smooth control, the designer modifies the system to achieve a continuous and smooth output.