64-424
Intelligent Robotics

https://tams.informatik.uni-hamburg.de/lectures/2018ws/vorlesung/ir

Marc Bestmann / Michael Görner / Jianwei Zhang

University of Hamburg
Faculty of Mathematics, Informatics and Natural Sciences
Department of Informatics
Technical Aspects of Multimodal Systems

Winterterm 2018/2019

Outline

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Introduction

The concept of fuzzy logic was introduced by Lotfi Zadeh (1965)

- Inspired by human information processing capabilities
- People do not require precise, numerical information input, yet they are capable of highly adaptive control

General assumption

- If feedback controllers could be programmed to accept noisy, imprecise input, they would be much more effective and perhaps easier to implement

- How important is it to be exactly right when a rough answer will do?

Fuzzy control (cont.)

- *Fuzzy* means: blurred, diffuse, vague, uncertain, . . .
- Fuzzy control uses fuzzy sets as mechanism for
  - Abstraction of unnecessary or too complex details
  - Troubleshooting of problems which are not easily solvable by a simple *yes* or *no* decision
  - Modeling of (*soft*) concepts without any sharp borders

Fuzzy control (cont.)

- Unsharp linguistic grading of terms like **"big"**, **"beautiful"**, **"strong"** . . .
- Human thinking models and behavior models with first-level logic
  - **Car driving:** *if*-*then*-rules
  - **Car parking:** Accurate up to a milimeter?
- Fuzzy speech instead of numerical description
  - "Brake 2.52 m ahead of the curve!" → only in machine systems
  - "Brake shortly before the curve!" → in natural language

Adaptive control methods

Fuzzy control is generally a good fit for realization of *adaptive control methods*

- Control can be understood as mapping from a sensor space onto actions
- In many cases it is *a priori* unknown, which measurement parameters are especially important for the choice of actions
- Some systems are very hard to describe in a mathematical way
- Often, sensor data is inaccurate, noisy and/or high dimensional

Adaptive control methods (cont.)

Models for adaptive control systems

- The creation of an ideal mapping between sensor space and actions is very difficult with classical methods of control engineering
- In order to control such systems, a simpler method needs to be used for description

- Neural networks
- Fuzzy-Controller

Linguistic variables

Linguistic variables are one of the main building blocks of fuzzy logic

- A *linguistic variable* is a variable, which can take on a range of linguistic terms
- A *linguistic term (value, label)* is the quantification of a term from natural language through a fuzzy set

- Many terms of natural language can be characterized through degree of membership related to fuzzy sets
- Therefore, fuzzy sets can be considered as the basic tool for modelling of *linguistic terms*

Linguistic variables (cont.)

Examples:

- Linguistic variable: "**SPEED**"
- Linguistic terms of "**SPEED**"
  "**high**", "**low**", "**rapid**", "**economical**"

- Linguistic variable: "**BUILDING**"
- Linguistic terms of "**BUILDING**"
  "**cottage**", "**bungalow**", "**skyscraper**"

Linguistic variables (cont.)

A **linguistic variable** is characterized through a quintuplet

$$(v, T(v), X, G, M)$$

With:

- v: the name of the variable
- $T(v)$: a set of linguistic terms of v, whereas each value is a fuzzy set in the universe X
- G: a syntax rule, which creates $T(v)$ from a set of basic terms
- M: a semantic rule, which maps its meaning to each value of $T(v)$

Characteristic function

Crisp sets can be defined through specification of their characteristic function:

$$\mu_{\mathcal{A}}(x) = \begin{cases} 1 & \text{for } x \in \mathcal{A} \\ 0 & \text{for } x \notin \mathcal{A}, \end{cases}$$

where $\mu_{\mathcal{A}} : X \to \{0, 1\}$

Membership function

For **fuzzy sets** A, a generalized characteristic function μ_A is used, which maps a real number $[0, 1]$ to each element $x \in X$:

$$\mu_A : X \to [0, 1]$$

- The function μ_A is called membership function (MF)
- It indicates the "degree", to which the element x belongs to the described unsharp set A ($\to$ fuzzy set)

Membership function (cont.)

Representation of membership functions

- Discrete representation
  - Fixed-size array
  - Saving of the MF-Values for the whole x-codomain

- Parametric representation
  - Functions with parameters (less space required)
  - Typical types: Singleton, triangular shape, trapezoid shape, bell curve, B-Spline basis function

Membership function (cont.)

Creation of the membership functions

- Context-dependent specification
  - Experimental, domain- and application specific
- Construction using sample data
  - Clustering
  - Interpolation
  - Curve Fitting (Least-squares)
  - Neural networks
- Knowledge acquisition through experts
  - One or several experts
  - Directly and indirectly

Fuzzy set

A **fuzzy set** A over a universe X is given through a mapping $\mu_A : X \rightarrow [0,1]$.
For all $x \in X$, $\mu_A(x)$ denotes the degree of affinity (membership) of x in A

The set of all elements from X with positive affinity to A is called **support** of a fuzzy set:

$$support(\mu_A(x)) = \{x \in X \mid \mu_A(x) > 0\}$$

Fuzzy set (cont.)

Example:

- The set of integer numbers approximately equal to 10:

$$A_{10} = (0.1, 7), (0.5, 8), (0.8, 9), (1.0, 10), (0.8, 11), (0.5, 12), (0.1, 13)$$

Fuzzy control

Main principles of fuzzy control

- Description of the desired control behaviour by means of colloquial, qualitative rules
- Quantification of linguistic values through fuzzy sets
- Rule evaluation through fuzzy logic methods (*fuzzy inference*) or interpolation

Fuzzy control (cont.)

In a fuzzy control system, the influence on dynamic circumstances of a fuzzy system is characterized by a set of linguistic description rules

IF (a set of conditions is satisfied)
THEN (a set of consequences can be infered)

Conditions (antecedents or premises) of the IF-part:
→ Linguistic variables from the domain of process states

Conclusions (consequences) of the THEN-part:
→ Linguistic variables from the control domain

Fuzzy control (cont.)

Main goals of fuzzy control

- **Intelligent control**
  - Use of expert knowledge
- **Linguistic control**
  - Control specifics are transparent
  - Advantageous for the human-machine interface
- **Parallel control**
  - Modularization
  - High processing performance

Fuzzy control (cont.)

Advantages

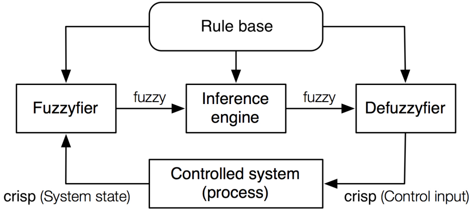
- Controller design is possible without any special knowledge about models of specific domains
- Controller design is efficient (up to a certain degree)
- Complies with real-time requirements

- Robust, even when using cheap and noisy sensors

Components of fuzzy control

A complete fuzzy controller consists of four major components

- Rule base
- Fuzzifier
- Inference engine
- Defuzzifier



Rule base

The rule base is the central component that stores expert knowledge

- It contains the control strategies in the form of IF-THEN rules

The rule base is considered a part of the knowledge base of the fuzzy controller, other components being:

- The input membership functions
  $\rightarrow$ required for *fuzzification* of crisp input values
- The output membership functions
  $\rightarrow$ required for *defuzzification* of the inference result(s)

Rule base (cont.)

Example:

Given a fuzzy control system with two inputs A and B and a single output C, the general representation of the rule base would be:

R_1: IF (x is A_1 OR y is B_1) THEN (z is C_1)

R_2: IF (x is A_2 OR y is B_2) THEN (z is C_2)

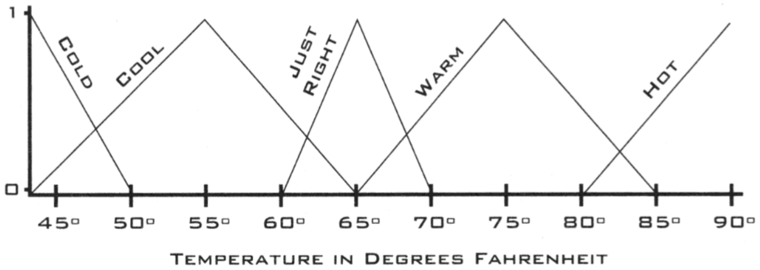
...

R_k: IF (x is A_k OR y is B_k) THEN (z is C_k)

Note: Inputs and outputs mentioned here are strictly fuzzy.

Fuzzifier

The fuzzifier converts the crisp input values into fuzzy representations based on the membership degree to established fuzzy sets



Fuzzifier (cont.)

- The established fuzzy sets and associated membership functions are designed to exploit the inherent inaccuracy of input data (e.g. from sensors)

- The fuzzifier approximates the human reasoning process
- While expert knowledge of the process to be controlled is helpful, it is not a requirement
- The overall implementation effort of the controller is reduced significantly

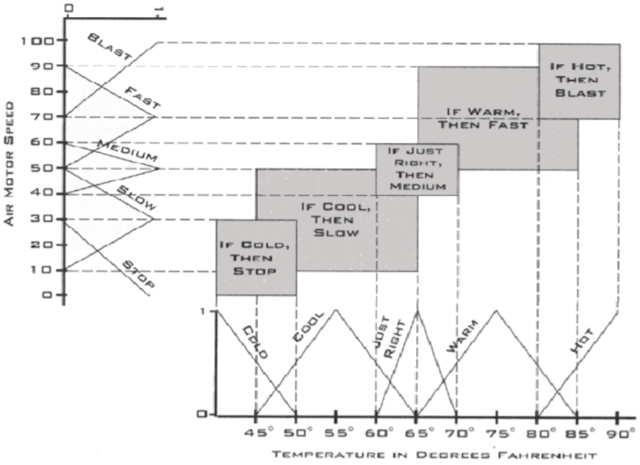
Inference engine

The inference engine processes the *fuzzified* input values based on evaluation of the rule base

- *All* rules within the rule base are evaluated
- The evaluation usually occurs in parallel (depends on implementation)

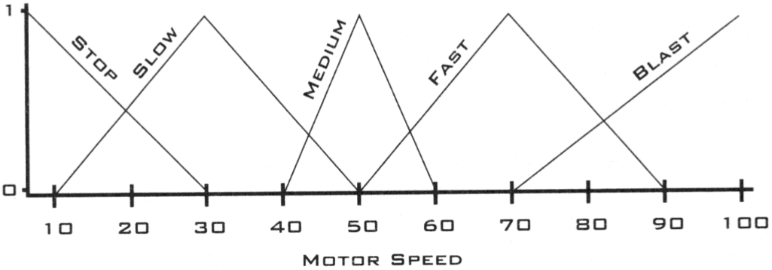
- All evaluated rules contribute to the fuzzy output value to some degree
- The contribution of most rules to the output value is 0
- The resulting fuzzy output value is a *union* of the results of all evaluated rules

Inference engine (cont.)



Defuzzifier

The defuzzifier converts the obtained fuzzy output value into a crisp representation based on the output membership functions



Defuzzifier (cont.)

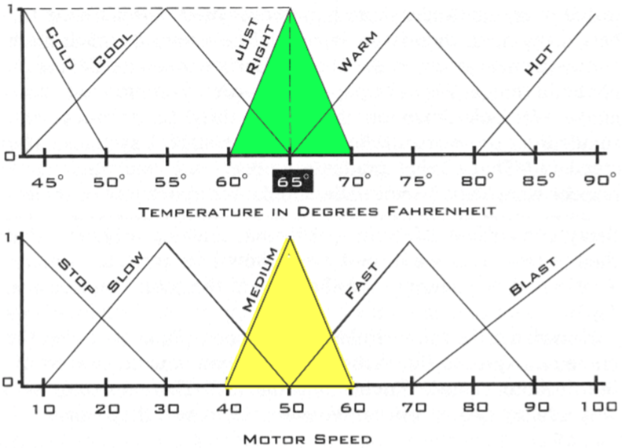
Several strategies exist for defuzzification

- The center of gravity (CoG) technique is very common

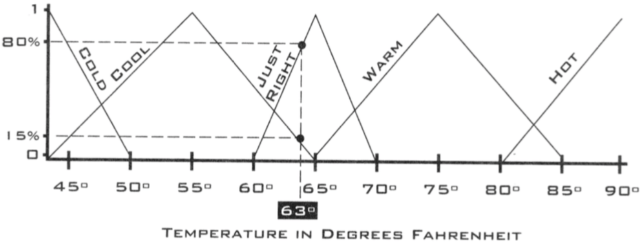
Other strategies include:

- Mean of maximum
  $\rightarrow$ The defuzzified result represents the mean value of all actions, whose membership functions reach the maximum
- Weighted average method
  $\rightarrow$ Formed by weighting each output by its respective maximum membership degree
- ...

Simple case

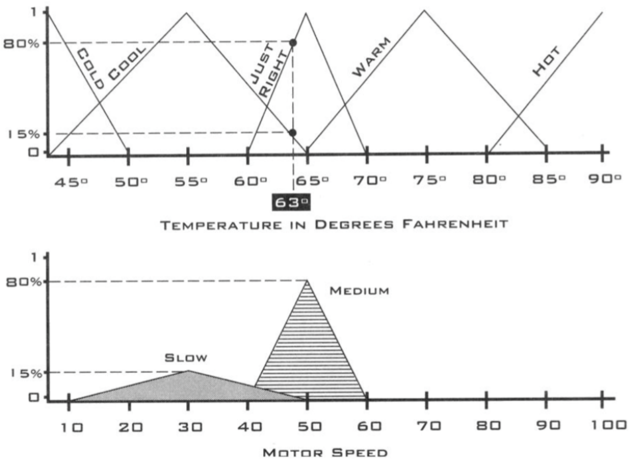

1
0
COLD
COOL
JUST RIGHT
WARM
HOT
45°
50°
55°
60°
65°
70°
75°
80°
85°
90°
TEMPERATURE IN DEGREES FAHRENHEIT
1
0
STOP
SLOW
MEDIUM
FAST
BLAST
10
20
30
40
50
60
70
80
90
100
MOTOR SPEED

General case

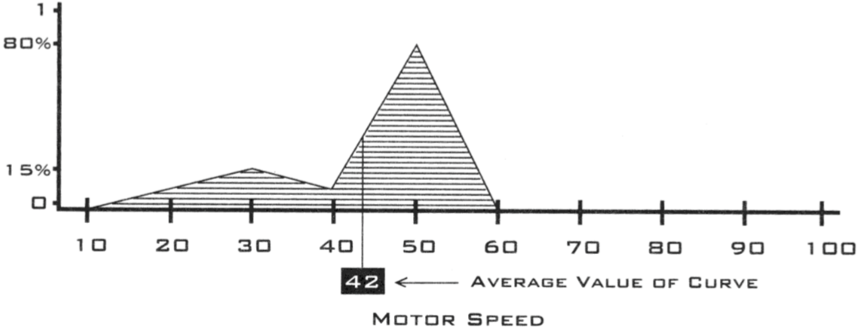


- IF temperature is **cool** THEN motor speed is **slow**
- IF temperature is **just right** THEN motor speed is **medium**

General case (cont.)



General case (cont.)



Curse of dimensionality

Fuzzy logic based control models (nonlinear modeling techniques) are affected by the *curse of dimensionality*

→ If the number of inputs grows, the cost of both implementing the rule base and obtaining an output value increase exponentially.

Summary

- Fuzzy logic provides a different way to approach a control problem
- It is based on natural language
- It allows to solve the problem without the need of a mathematical model
- FL based controllers require less implementation effort and are thus usually cheaper

- FL is inherently tolerant of imprecise data
- It can model nonlinear functions of arbitrary complexity

- Fuzzy logic can be combined with conventional control techniques

Summary (cont.)

- Fuzzy logic is not a cure-all!
- Fuzzy logic is a convenient way to map an input space to an output space
- However, many controllers can do a fine job without it
- Fuzzy logic *can* be a powerful tool for dealing with imprecision and nonlinearity

Literature list

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Fuzzy Thinking: The New Science of Fuzzy Logic.
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