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研究ノート

# ファジー理論
# 制御システム系への応用

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# Fuzzy Logic in Control System

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## 1．Introduction

Fuzzy logic belongs to Artificial Intelligence Study. Fuzzy logic aims realizing a method to represent the human-like reasoning in terms of a natural language. Its representations are converted to a form readily translated into machine codes for digital computers. Nowadays, fuzzy logic has been deployed into industrial applications because of its efficiency, reliability, and simpleness handling ambiguous, unstable, and heterogeneous analog world phenomena. The basic of fuzzy logic and its applications in control systems are introduced in this paper, and a simple control system is built in a software simulation program to contrast the fuzzy logic control technology with the traditional control technology.

## 2．Fuzzy Logic

### *2.1. Feature*

Information that we handle is not always certainly expressed. For example, a sentence " The person is happy．" can not be sharply described. However, we humans make sense out of this type of vague sentence. Ordinary computations utilize implicit programming languages to deal with decision makings. Therefore, classifying an object with unclear information is a considerably difficult task. By forcing a clear answer, Yes or No, will cause information losts because the expression " happy " must contain a degree of happiness that he/her is currently enjoying. Therefore, having a computer system with capability of manipulating such an uncertainty will solve wide range of issues. Fuzzy logic was introduced as a mathematical theory in 1965 by Dr. Lotfi Zadeh. The logic has been applied to practical systems such as electrical motor controllers etc.

### *2.2. Logic*

The fuzzy logic utilizes fuzzy sets. Fuzzy sets does not impose rigid membership requirements upon objects within a set. An object is not either completely in the set or not in the set. A fuzzy set has flexible membership requirements that allow a partial membership in a set or sets. The traditional computation set has a degree of an object with strictly 0 or 1.　Contrarily, a fuzzy set may take any value between 0 and 1, which expresses gradual transitions from a membership to non-membership.

Figure 1 shows an example of a comparison of a traditional set and a fuzzy set.　The traditional set asserts " 1 " for a man weighing 80 Kg (graph on left).　On the other hand, the fuzzy set asserts " 0.5 " (graph on right).

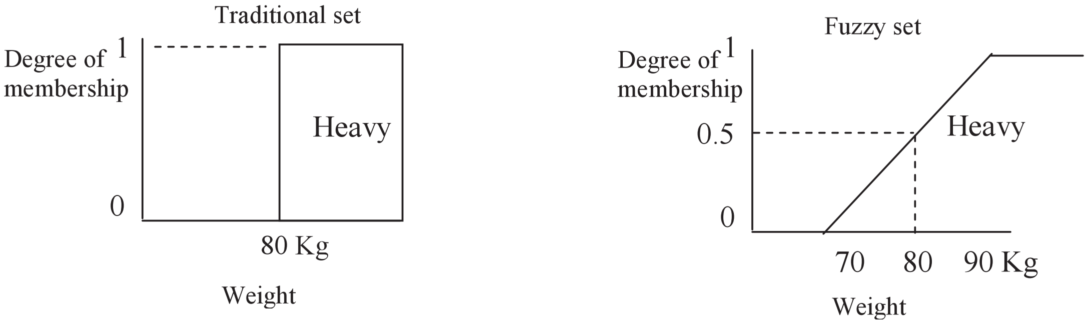



Figure 1.  Traditional Set and Fuzzy Set

Figure 2 shows a traditional and a fuzzy version of sets " LIGHT " and " HEAVY ".　Notice an abrupt change of membership in the traditional " LIGHT " and " HEAVY " sets at a weight of 80 Kg. But, the fuzzy " LIGHT " and " HEAVY " sets allow a gradual change from " LIGHT " to " HEAVY " for a man weighing between 70 Kg and 90 Kg.
Is a man weighing 75 Kg LIGHT or HEAVY? It is ambiguous. People would say he is somewhat LIGHT, and they would say he is somewhat HEAVY. Traditional sets do not model this ambiguity well at all. However, fuzzy sets, which allow partial memberships, provide a way for a computer to deal with this ambiguity by classifying the man as somewhat LIGHT and somewhat HEAVY at the same time.

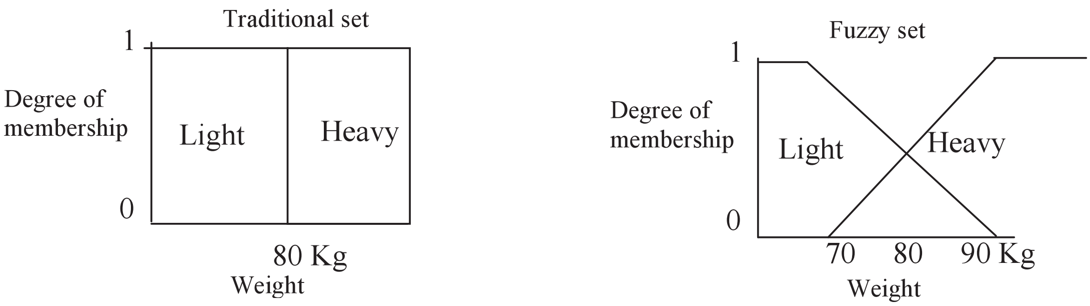



Figure 2.  Non-Overlapping and Overlapping Sets

*2.3. Membership Functions*
Each fuzzy set has a corresponding membership function that returns degrees of memberships for a given value of a variable. Membership functions may be any form as long as a returned

value remains in the range between 0 and 1, expressed as “ [0, 1 ] ”.
To define a variable, “ Weight ”, the following notation is employed to obtain a degree of membership:

“ Weight IS HEAVY ”

This surprisingly fits to our natural language.

### *2.4. Fuzzy Logic Operators*

Table 1 introduces the most common fuzzy logic operators. Fuzzy logic operators are similar to Boolean operators. However, fuzzy logic operators have different definitions. The three basic fuzzy logic operators are AND, OR and NOT. Given two expressions a and b, the operators are defined in the table:

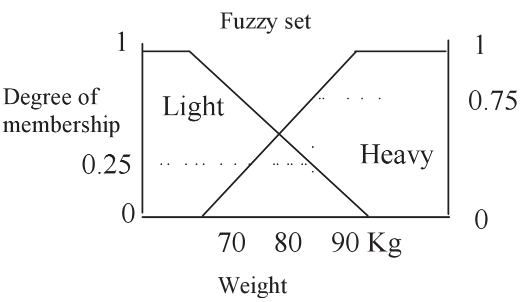
| **Operator** | **Calculation** | **Definition** |
|---|---|---|
| *a* AND *b* | min (*a, b*) | Take a smaller value |
| *a* OR *b* | max (*a, b*) | Take a larger value |
| NOT *a* | 1.0 – *a* | Complement of *a* |

Table 1. Fuzzy Operators

For example, the expression (Weight IS HEAVY) OR (Weight IS LIGHT) is evaluated as :

max ((Weight IS HEAVY), (Weight IS LIGHT))

where the membership functions for “ HEAVY ” and “ LIGHT ” are given degrees of a membership of “ Weight ” in each set.




“(Weight IS Light) OR (Weight IS HEAVY)” is expressed as “max(0.25,0.75)”. “0.75” is asserted.

Figure 3. Fuzzy Logic Operators

## 3. Fuzzy Logic in Control System

Table 2 shows industrial applications which fuzzy logic may and do provide good solutions. The control field is one of the most promising fields in application of fuzzy logic theory（Singh and Yang p155）.

| Automotive Controls | Consumer Electronics/Home Appliances |
|---|---|
| Anti-Lock Brake Control | Auto focus Cameras |
| Automatic Transmission Control | Washing Machines |
| Fuel Injection Control | Vacuum Cleaners |
| Spark Advance Control | Refrigerators |
| **Medicine** | **Aerospace** |
| X-ray Analysis | Vehicle Attitude Control |
| Endoscopic Tools | Obstacle Avoidance |
| Laboratory Analysis Equipment | Temperature Control |
| **Industrial Control** | **Business** |
| Welding Robot Control | Box Sorting |
| Blast Furnace Operation | Job Shop Scheduling |
| Power Plant Load Prediction | Financial Analysis |
| Plasma Etching | Automatic Credit Scoring |
| **Computers** | **Civil Engineering** |
| Data Retrieval | Earthquake Hazard Prediction |
| Speech Recognition | Structural Motion Control |
| Machine Vision | Structural Safety Assessment |
| Optical Character Recognition (OCR) | Subway Control |

Table 2. Fuzzy Logic Applications (Togai p. 7)

Advantages of fuzzy logic controller systems are discussed in this section followed by a description of a conceptual fuzzy logic control system.

*3.1. Fuzzy Logic Controller Advantages*

Advantages of Fuzzy Logic Controller（FLC）over conventional control systems are listed below:

１）Easy development

Methods applied for creating rules for FLC implement the “ rule of thumb ” experience, which is a major advantage over the traditional control system designing. Following steps are required to design FLC :

1．Create control rules using knowledge and experience
2．Describe them in simple words
3．Build models
4．Design the system

Now again, designing traditional control system requires :

1. Understand the physical system and its control requirement
2. Build mathematical models
3. Describe relationships between input and output variables
4. Design the system
5. Optimize parameters

Furthermore, modifying a design of a traditional control system requires not only changing its model but also redesigning its parameters. However, adjustments are necessary for a fuzzy control system only in its rules instead.

2) Good performance with complicated nonlinear systems

Linearization and simplified assumptions are employed for designing a traditional controller to model complicated nonlinear systems. However, their performance is limited in a certain range and applications. In contrast, FLC deals with complicated nonlinear systems by rules or membership functions. Thus, FLC can achieve proper controls over a wide range of conditions.

3) Higher reliability

A traditional control system relies on system parameters. If one of the parameters fails, the entire system may fail. The failure frequently occurs in case the system is in an unstable environment(e.g., with a high level of noise). With FLC, control commands are based on several fuzzy rules. Consequently, an FLC system still works even though one of the rules fails. By this means, an FLC system is more reliable than a traditional control system because it is more capable to tolerate against noises, environmental changes, and sensor failures.

4) Faster Operation

A parallel structure of fuzzy computations achieves quick system responses. More than one inputs and outputs are evaluated simultaneously. Also, fuzzy logic translates complex problems to simple fuzzy inference rules, which makes control computations executed in a shorter period of time.

### *3.2. Conceptual Fuzzy Logic Control System*

A fuzzy controller is structured by four major components, fuzzification interface, decision making unit (fuzzy inference engine), defuzzification interface, and knowledge base. Following figure depicts the conceptual block diagram (Singh and Yang p. 157) :

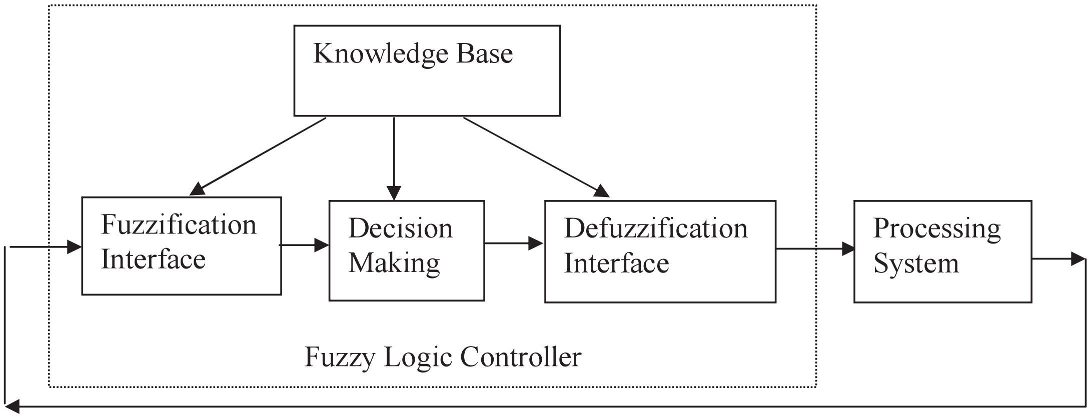



Figure 4.　Conceptual Fuzzy Logic Controller

- Knowledge Base

Knowledge Base contains control rules, inference methods, and data processing knowledge offering knowledge necessary for operations in other units. The control rules may be acquired from expert's experiences, control engineering knowledge in other systems, or operator's control actions. Knowledge Base generates knowledge of how to define linguistic variables, choose proper membership functions, and manipulate fuzzy data and fuzzy relations.

- Fuzzification Interface

Input data in the real world is uncertain in general such as flow rates, temperature, pressure etc. Therefore, the system needs to transform the data into fuzzy sets to apply fuzzy inference rules. A simple and intuitive method of fuzzification is to convert ambiguous data into a fuzzy singleton. A fuzzy singleton is a fuzzy set whose membership function equals to 1 at one point and 0 at other points, which is the same as crisp data in a traditional control system.

- Decision-Making Unit（Fuzzy Inference Engine）

Decision-Making unit mimics human decision-making. The system makes decisions using fuzzy logic and approximate reasoning（e.g., MIMO, or multi-input/multi-output system, is employed.）.

- Defuzzification Interface

Fuzzy control outputs are converted to crisp control commands by Defuzzification Interface. There are several methods to perform this task. The center of area（COA）and the mean of maximum（MOM）are the most common methods. The COA method produces the center of gravity of a possible distribution of the final control action.

## 4．Simulation of Simple Fuzzy Logic Control System

A simulator has been built for this research utilizing a fuzzy logic tool, " Fuzzy CLIPS ", an extension of the CLIPS（C Language Integrated Production System）expert system shell from NASA（National Aeronautics and Space Administration）.　The simulation is a simple air-conditioning system with just a heater. The mechanism is:

1. An empty room is provided with air of temperature of 0 degrees C at the initial stage.
2. A heater is controlled either by a traditional control system or a fuzzy logic control system.
3. The goal of the system is to make the room temperature 24 degrees C.
4. The room temperature gradually goes down to 0 degrees C as the heater turns off assuming the outside air temperature is 0 degrees C.
5. The room temperatures are plotted in a time series graph.

### *4.1. Fuzzy Logic Expressions in Fuzzy CLIPS*

The followings are essential parts of 104 lines of codes written in the format of the fourth generation language (an extension of C), Fuzzy CLIPS. The codes will be much larger if simple C language is adopted.

<u>Definitions of initial values</u>

```
(defglobal
 ?*HEATER-TEMP* = 40.0        ; Heater's air temperature
 ?*ROOM-FACTOR* = 0.05        ; Decided by a room (e.g., size)
 ?*COUNTER* = 0               ; Time
 ?*ROOM-TEMP* = 0             ; Initial room temperature
 ?*REFRIG-FACTOR* = 0.05      ; Room Temp. descending factor
)
```

<u>Definition of a fuzzy value "cold"</u>

```
(deftemplate Fuzzy-RoomTemp
 -1 28 Celsius    ; Declaring the temp is between -1 and 28 degrees C.
 (                ;
  (cold (z 10 23)); "cold" completes at 10 degrees C with a value 1
 )                ; and ends at 23 degrees C with a value 0.
)                 ;
```

* "Z" represents the shape of plots explained in this section.

<u>Main part of simulator</u>

```
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;; Simulation ;;;;;;;;;;;;;;;;;;;;;;;;;;;;
(deffunction Simulator(?HeaterPower)
 ;---------------------------------------;
 ; Room temp.  Adjusted by HeaterPower  ;
 ;---------------------------------------;
 (bind ?*ROOM-TEMP* (+ ?*ROOM-TEMP* (* ?*ROOM-FACTOR*
                 (* ?*HEATER-TEMP* ?HeaterPower))))
 ;--------------------------------------------------------;
 ; Room temp.  Decreases 10 % of current room temperature ;
 ; due to the refrigeration by outside temperature.       ;
 ;--------------------------------------------------------;
 (bind ?*ROOM-TEMP* (- ?*ROOM-TEMP* (* ?*ROOM-TEMP* ?*REFRIG-FACTOR*)))
 (printout t "  New room temperature: " ?*ROOM-TEMP* crlf)
 (assert (RoomTemp ?*ROOM-TEMP*))
)
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
```

<u>Fuzzification Interface</u>

```
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;; Fuzzification ;;;;;;;;;;;;;;;;;;;;;;;;;;;;
(defrule Fuzzification
```

```
 ?f1 <- (RoomTemp ?)
 =>
  (retract ?f1)
  (assert (Fuzzy-RoomTemp (pi 1 ?*ROOM-TEMP*)))
  (printout t "  Fuzzified temperature is asserted."crlf)
)
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
```

## Fuzzification Inference (decision Making)

```
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;; Fuzzy Inference ;;;;;;;;;;;;;;;;;;;;;;;;;;;
(defrule Cold-PowerStrong
 (Fuzzy-RoomTemp cold)
 =>
  (assert(Fuzzy-HeaterPower strong))
)
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
```

## Defuzzification Interface

```
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;; Defuzzification ;;;;;;;;;;;;;;;;;;;;;;;;;;;;
(defrule Defuzzify-HearterPower
 ?f1 <- (Fuzzy-HeaterPower ?)
 =>
  (bind ?HeaterPower (moment-defuzzify ?f1))
  (assert (HeaterPower ?HeaterPower))
  (retract ?f1)
)
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
```

Following is an output from the program showing an example of a fuzzy value “cold” with asserting 22 degrees C:

```
; defuzzified temp value: 22.0
;
; Fuzzy Value: temp
; Linguistic Value: ??? (2),  cold (c)
;
;  1.00cccccccccc                       2
;  0.95          ccc
;  0.90             ccc
;  0.85                c
;  0.80                 cc
;  0.75                   c                2
;  0.70                    cc
;  0.65                      c               2
;  0.60                       c
;  0.55                        c
;  0.50                         c
;  0.45                          c
;  0.40                           c
;  0.35                            c
;  0.30                             cc
;  0.25                               c     2
;  0.20                                cc
;  0.15                                  c
;  0.10                                   ccc   2
;  0.05                                      ccc
;  0.00222222222222222222222222222222222222222222222   cccccccccc
;      |----|----|----|----|----|----|----|----|----|----|
;     8.00      11.60     15.20     18.80     22.40     26.00
;
; Universe of Discourse:  From   8.00  to   26.00
```

Figure 5.  Fuzzy Value “cold” in Simulation

As explained in“ Definition of a fuzzy value cold ”, a fuzzy value“ cold ”depicts a“ Z ”shape curve, returns1.0 at 10 degrees C or lower and returns 0 at 23 degrees or higher. Corresponded values between 0 and 1 are returned along the “ Z ” shape curve at between 10 and 23 degrees C.

### *4.2. Simulation Results*

Fashion of temperatures from two systems, a traditional control system and a fuzzy control system, are summarized. Figure 6 indicates that the traditional control achieves the target temperature 22 degrees C in shorter time, 20 counts. In contrast, the fuzzy control achieves the target temperature in around 60―70 counts. But, the plots from the traditional control shows instability after reaches the target temperature. This result reminds us of a typical heating or cooling problem with conventional air-conditioners in small rooms. Unstable temperature not only causes damages to goods or people inside but also produces inefficiency in a system.

| Time | Traditional [Deg. C] | Fuzzy[Deg. C] | Time | Traditional [Deg. C] | Fuzzy[Deg. C] |
|---|---|---|---|---|---|
| 0 | 0.0 | 0.0 | 21 | 23.2 | 18.2 |
| 1 | 1.9 | 1.4 | 22 | 23.9 | 18.6 |
| 2 | 3.7 | 2.7 | 23 | 24.6 | 18.9 |
| 3 | 5.4 | 4.0 | 24 | 23.4 | 19.3 |
| 4 | 7.0 | 5.2 | 25 | 24.1 | 19.6 |
| 5 | 8.6 | 6.4 | 26 | 22.9 | 19.9 |
| 6 | 10.1 | 7.4 | 27 | 23.7 | 20.2 |
| 7 | 11.5 | 8.5 | 28 | 24.4 | 20.5 |
| 8 | 12.8 | 9.5 | 29 | 23.2 | 20.7 |
| 9 | 14.1 | 10.4 | 30 | 23.9 | 20.9 |
| 10 | 15.2 | 11.3 | 31 | 24.6 | 21.1 |
| 11 | 16.4 | 12.1 | 32 | 23.4 | 21.3 |
| 12 | 17.5 | 12.9 | 33 | 24.1 | 21.5 |
| 13 | 18.5 | 13.6 | 34 | 22.9 | 21.7 |
| 14 | 19.5 | 14.3 | 35 | 23.7 | 21.8 |
| 15 | 20.4 | 15.0 | 36 | 24.4 | 22.0 |
| 16 | 21.3 | 15.6 | 37 | 23.2 | 22.1 |
| 17 | 22.1 | 16.2 | 38 | 23.9 | 22.2 |
| 18 | 22.9 | 16.7 | 39 | 24.6 | 22.3 |
| 19 | 23.7 | 17.3 | 40 | 23.4 | 22.4 |
| 20 | 24.4 | 17.7 | 41 | 24.1 | 22.5 |

Table 3. Simulation Results (partial)

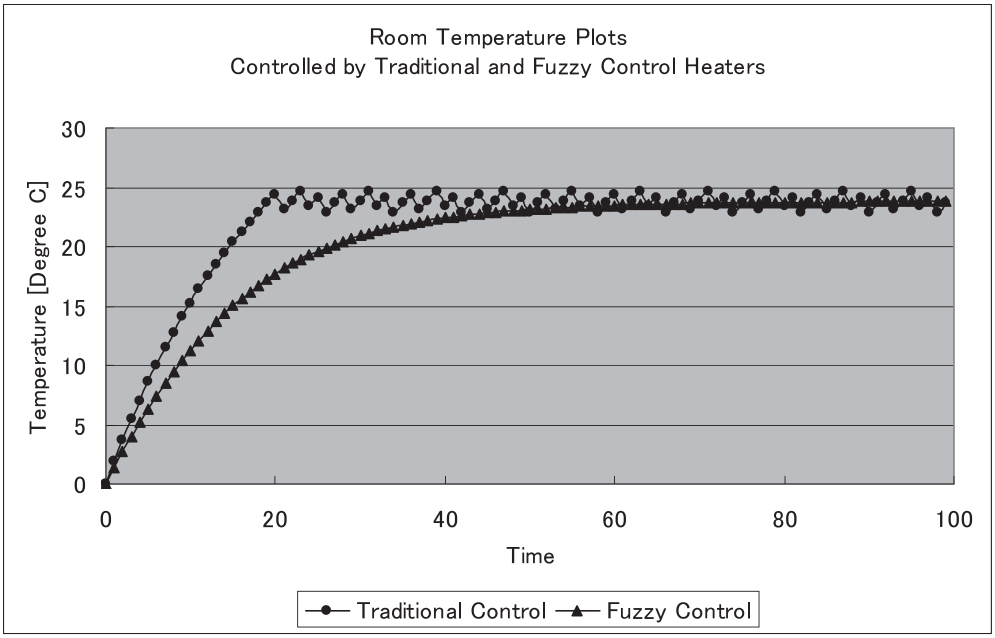



Figure 6. Plotted Simulation Results（Traditional and Fuzzy）

Figure 7 shows a result from a modified system adopting fuzzy logic with“ rough logic ”sets. The graph indicates that the slow response with fuzzy logic control in Figure 6 is rectified by adding the rough logic technology, which suggests that fuzzy logic may be tuned up or combined with other logics to achieve a better performance.

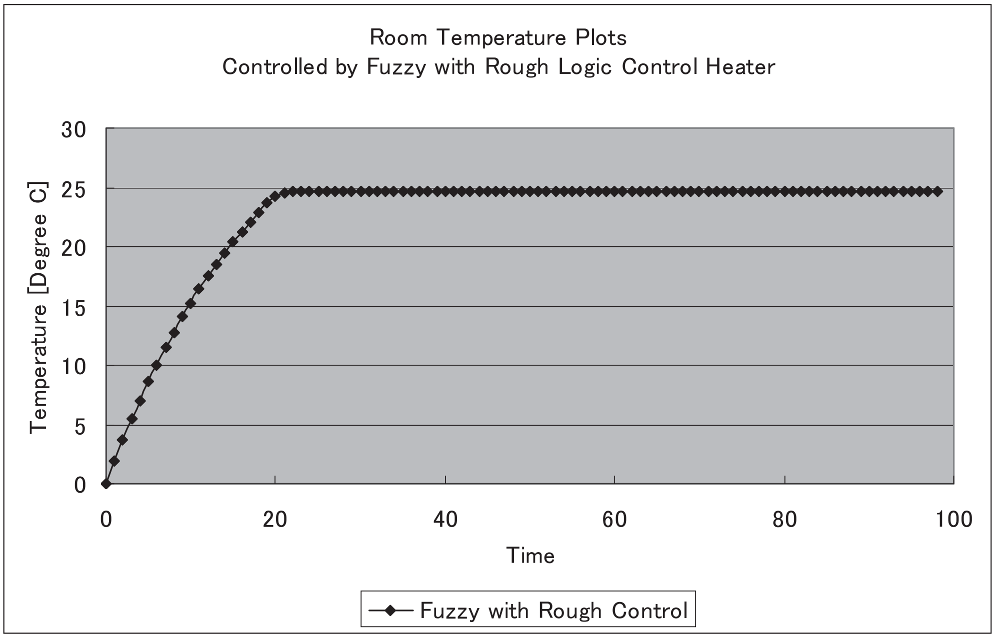



Figure 7. Plots from Fuzzy with Rough Logic Control Simulation

## 5. Conclusion

Fuzzy logic in control systems is introduced with its application examples and compared with a traditional logic in a software simulator. Fuzzy logic effectively solves issues in traditional control systems which handles mere crisp data instead of data with fuzziness. Control systems need to handle unstable analogue values with erroneous and heterogeneous features. Human-beings are naturally good at dealing with such uncertainty. Therefore, fuzzy logic control systems can achieve effective and reliable performances by employing human-like perceptions, processes, or reasoning. An aspect of fuzzy logic observed in the software simulator suggests its high efficiency in electrical or mechanical control systems. A research by Air and Energy Engineering Research Laboratory insists that efficiency of industrial motors will be gained by 1－4%by applying fuzzy logic(Cleland p. 3).  Gaining efficiency of industrial motors in worldwide will result in saving massive energy consumptions. Deploying sophisticated control technologies such as fuzzy logic control will lead efficient control systems and may facilitate resolving the energy and environmental issues.

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