

# Table of Contents

## Abstract

## Acknowledgments

|  |           |
|--|-----------|
| <b>List of Tables .....</b>                                  | <b>x</b>  |
| <b>List of Figures .....</b>                                 | <b>xi</b> |
| <b>Chapter 1 INTRODUCTION .....</b>                          | <b>1</b>  |
| <b>Chapter 2 FUZZY CONTROLLER AND FUZZY CHIPS .....</b>      | <b>5</b>  |
| 2.1 Fuzzy Logic and Fuzzy Control .....                      | 5         |
| 2.1.1 Fuzzy Sets .....                                       | 5         |
| 2.1.2 Basic Fuzzy Set Operations .....                       | 7         |
| 2.1.3 Fuzzy Logic and Fuzzy inference .....                  | 9         |
| 2.2 The Basic Architecture of a Fuzzy Logic Controller ..... | 12        |
| 2.2.1 Knowledge Base .....                                   | 13        |
| 2.2.2 Fuzzification Interface .....                          | 14        |
| 2.2.3 Fuzzy inference Engine .....                           | 15        |
| 2.2.4 Defuzzification Interface .....                        | 19        |
| 2.3 Fuzzy Logic Controller Hardware Implementation .....     | 20        |
| 2.4 Summary .....  | 25        |
| <b>Chapter 3 ANALOG FUZZY BUILDING BLOCKS .....</b>          | <b>27</b> |
| 3.1 Basic CMOS Circuits .....                                | 28        |
| 3.1.1 The MOS Transistor .....                               | 28        |

|   |    |
|---|----|
| 3.1.2 MOS Switch .....  | 31 |
| 3.1.3 MOS Source Follower .....                                   | 32 |
| 3.1.4 Current Source and Current Mirror .....                     | 32 |
| 3.1.5 Differential Amplifier .....                                | 33 |
| 3.2 Fuzzy Membership Function Circuit .....                       | 35 |
| 3.2.1 Two Early Implementations of MFC .....                      | 36 |
| 3.2.2 Another Membership Function Circuit .....                   | 38 |
| 3.2.3 The MFC Flexibility Analysis .....                          | 41 |
| 3.3 Maximum and Minimum Circuits .....                            | 46 |
| 3.3.1 Circuit Realization of Maximum and Minimum Operations ..... | 46 |
| 3.3.2 The Circuits Calculation Accuracy .....                     | 48 |
| 3.4 Defuzzification Circuit .....                                 | 50 |
| 3.4.1 Voltage Follower-aggregation Circuit .....                  | 50 |
| 3.4.2 Voltage-current Converter .....                             | 52 |
| 3.4.3 Defuzzification Circuit .....                               | 53 |
| 3.4.4 Further Discussion .....                                    | 53 |
| 3.5 Summary .....   | 54 |

## **Chapter 4 CHIP REALIZATION AND TESTING ..... 57**

|   |    |
|---|----|
| 4.1 Test Results of Fuzzy Building Blocks .....                       | 57 |
| 4.1.1 The MIETEC 2.4mm CMOS Process .....                             | 58 |
| 4.1.2 Membership Function Circuits .....                              | 59 |
| 4.1.3 Min, Max Operators and Fuzzy Inference Engine .....             | 63 |
| 4.1.4 Defuzzification Circuit .....                                   | 66 |
| 4.2 A Three-input Two-output Fuzzy Controller .....                   | 69 |
| 4.3 A Reconfigurable Fuzzy Logic Controller .....                     | 74 |
| 4.3.1 Analog Multiplexers and a Reconfigurable Inference Engine ..... | 75 |

|   |            |
|---|------------|
| 4.3.2 A Reconfigurable Fuzzy Logic Controller .....           | 77         |
| 4.4 Summary .....   | 81         |
| <b>Chapter 5 EXPERIMENTAL APPLICATIONS .....</b>              | <b>83</b>  |
| 5.1 A Fuzzy Car-wheel Damping System .....                    | 83         |
| 5.1.1 A Car-wheel Damping System .....                        | 83         |
| 5.1.2 Fuzzy Control Method .....                              | 84         |
| 5.1.3 Control Simulation .....                                | 88         |
| 5.2 Application in a Teleautonomous Robot System .....        | 89         |
| 5.2.1 Collision Avoidance with a Fuzzy Logic Controller ..... | 90         |
| 5.2.2 Experimental Platform MORIA .....                       | 92         |
| 5.2.3 Control Strategies with the Fuzzy Chips .....           | 93         |
| 5.2.4 Experiment Verification .....                           | 97         |
| 5.3 Summary .....   | 100        |
| <b>Chapter 6 CONCLUSIONS .....</b>                            | <b>101</b> |
| <b>Bibliography .....</b>                                     | <b>103</b> |

## **List of Tables**

|   |    |
|---|----|
| Table 2-1 The typical performance of some analog fuzzy chips .....                | 25 |
| Table 4-1 SPICE level 3 parameters of MIETEC 2.4 $\mu\text{m}$ CMOS process ..... | 58 |
| Table 4-2 Fuzzy rules used for function generation .....                          | 78 |

# List of Figures

|             |  |    |
|-------------|--|----|
| Figure 2.1  | Diagrammatic representation of a fuzzy set .....                         | 6  |
| Figure 2.2  | Linguistic variable “air temperature” .....                              | 7  |
| Figure 2.3  | Parallel computation in a rule-based system .....                        | 12 |
| Figure 2.4  | The basic configuration of a fuzzy logic controller (FLC) .....          | 13 |
| Figure 2.5  | Matching a sensor reading with a membership function .....               | 15 |
| Figure 2.6  | Fuzzy inference with Mamdani’s technique .....                           | 18 |
| Figure 2.7  | Four types of membership functions used in fuzzy hardware system .....   | 23 |
| Figure 2.8  | A membership function circuit and its input-output characteristics ..... | 24 |
| Figure 3.1  | The MOS transistors .....  | 28 |
| Figure 3.2  | The schematic of a neuron-MOSFET .....                                   | 30 |
| Figure 3.3  | A CMOS switch .....  | 31 |
| Figure 3.4  | A MOS source follower .....  | 31 |
| Figure 3.5  | MOS current sources .....  | 32 |
| Figure 3.6  | A MOS differential amplifier .....                                       | 33 |
| Figure 3.7  | Schematics of MOS differential amplifiers with different loads .....     | 34 |
| Figure 3.8  | MFC by using differential amplifiers and a neural-MOSFET amplifier ..    | 36 |
| Figure 3.9  | A reconfigurable fuzzy membership function circuit .....                 | 37 |
| Figure 3.10 | HSPICE simulation results of the MFC shown in Fig. 3.9 .....             | 38 |
| Figure 3.11 | A MFC implemented with coupled differential amplifier .....              | 39 |
| Figure 3.12 | The five operating regions of the MFC shown in Fig. 3.11 .....           | 41 |
| Figure 3.13 | HSPICE simulation results of four types of membership function. ....     | 43 |
| Figure 3.14 | Changing the slopes of a membership function with M11 and M12 .....      | 44 |
| Figure 3.15 | The size of M12 affects the width of II” only .....                      | 44 |
| Figure 3.16 | The size of M11 affects the width of II’ .....                           | 44 |

|             |   |    |
|-------------|---|----|
| Figure 3.17 | Simulation result of a seven-term MFC   | 45 |
| Figure 3.18 | HSPICE output for the pulse response of the MFC                                 | 45 |
| Figure 3.19 | Schematics of (a) <i>max</i> and (b) <i>min</i> operators                       | 47 |
| Figure 3.20 | HSPICE outputs of (a) <i>max</i> and (b) <i>min</i> operators                   | 48 |
| Figure 3.21 | HSPICE outputs of the transient analysis of <i>max</i> and <i>min</i> operators | 49 |
| Figure 3.22 | The block diagram of a voltage follower-aggregation circuit                     | 51 |
| Figure 3.23 | (a) A CMOS transistor pair and (b) a voltage-current converter                  | 52 |
| Figure 3.24 | The diagram of a defuzzifier  | 54 |
| Figure 3.25 | HSPICE simulation result of the transient analysis of the defuzzifier           | 55 |
| Figure 4.1  | Membership functions with different shapes                                      | 59 |
| Figure 4.2  | A 5-term membership function generator  | 60 |
| Figure 4.3  | Outputs of the membership function circuit shown in Fig. 4.2(c)                 | 60 |
| Figure 4.4  | Four types of membership function realized with the circuit of Fig. 3.10.       | 61 |
| Figure 4.5  | Membership functions with various slopes  | 62 |
| Figure 4.6  | Fuzzification with 5 membership functions                                       | 63 |
| Figure 4.7  | Pulse response of an MFC shown in Fig. 3.10                                     | 63 |
| Figure 4.8  | DC measurement of a 3-input max operator  | 64 |
| Figure 4.9  | A fuzzy rule block  | 65 |
| Figure 4.10 | The outputs of a three-rule block with different input conditions               | 66 |
| Figure 4.11 | Photomicrograph of a 9-term defuzzifier chip                                    | 67 |
| Figure 4.12 | Comparison of the defuzzification results                                       | 67 |
| Figure 4.13 | Pulse response of the defuzzifier chip  | 68 |
| Figure 4.14 | A three-input two-output fuzzy logic controller                                 | 70 |
| Figure 4.15 | Fuzzy sets definitions in the fuzzy chip  | 71 |
| Figure 4.16 | Implemented fuzzy rules in the 3-input 2-output FLC                             | 71 |
| Figure 4.17 | Control surfaces of OUTPUT_1 in the FLC shown in Fig. 4.14                      | 72 |
| Figure 4.18 | Control surfaces of OUTPUT_2 in the FLC shown in Fig. 4.14                      | 73 |
| Figure 4.19 | Schematic diagram of an analog multiplexer                                      | 74 |
| Figure 4.20 | Diagram of a reconfigurable inference engine                                    | 75 |

|   |    |
|---|----|
| Figure 4.21 Thirteen antecedents equally distributed over the rule space .....        | 76 |
| Figure 4.22 Photomicrograph of the analog reconfigurable fuzzy logic controller ..... | 76 |
| Figure 4.23 Function generated by the fuzzy controller and its control rules .....    | 77 |
| Figure 4.24 Examples of the functions generated by the fuzzy logic controllers .....  | 78 |
| Figure 4.25 Examples of the control surfaces and the related fuzzy rules .....        | 79 |
| Figure 4.26 Pulse response of a reconfigurable fuzzy logic controller .....           | 80 |
| Figure 4.27 The influence of $V_r$ on the output of the fuzzy chip .....              | 82 |
|   |    |
| Figure 5.1 A car-wheel damping system .....   | 85 |
| Figure 5.2 Membership functions of the inputs H and W .....                           | 85 |
| Figure 5.3 The layout of subcontroller “comfort” .....                                | 86 |
| Figure 5.4 A synthetic road environment for one of simulation run .....               | 87 |
| Figure 5.5 Comparison of the simulation results .....                                 | 88 |
| Figure 5.6 A conventional teleoperation and a teleautonomous system .....             | 90 |
| Figure 5.7 An experimental platform — mobile robot MORIA .....                        | 92 |
| Figure 5.8 Sensor arrangement in the platform MORIA .....                             | 93 |
| Figure 5.9 Eight kinds of local environment perceptual with 3 sensors .....           | 93 |
| Figure 5.10 Block diagram of the control strategy I .....                             | 94 |
| Figure 5.11 Fuzzy control system with control strategy I .....                        | 95 |
| Figure 5.12 Block diagram of the control strategy II .....                            | 98 |
| Figure 5.13 Robot navigation with a teleautonomous system .....                       | 99 |