Microprocessors and Microsystems 44 (2016) 22–27

Contents lists available at ScienceDirect

Microprocessors and Microsystems

journal homepage: www.elsevier.com/locate/micpro

Implementation of a microcontroller-based simplified FITA-FIS model

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ARTICLE INFO

Article history:
Received 24 September 2015
Accepted 17 November 2015
Available online 2 December 2015

Keywords:
Fuzzy control
Fuzzy system
Fuzzy logic
Microcontroller
ARM

ABSTRACT

The paper describes basic approach to building a general purpose MISO-FITA (multiple inputs single output rule based system) fuzzy logic inference system. It is also discussed classic and simplified models of the inference systems and some optimization methods of its architecture. The fuzzy engine of the proposed system is based on simplified Mamdani's fuzzy inference model. It has been implemented on the sample platform based on ARMv7 Cortex-M4 microcontroller. The performance of the fuzzy inference system, defined as a time to obtain an output crisp inference result, is higher or comparable to another software and hardware solutions. For proposed system it even takes 10 μs.

1. Introduction

Fuzzy inference systems can be implemented in hardware or software. The hardware implementation of the system requires a dedicated hardware platform based on an FPGA, a CPLD or an ASIC chip [1–5]. An inference result in these systems is computed in the shortest time, but the system is not so flexible as a software implementation. A software solution of a fuzzy inference system uses usually a general purpose microcontroller or a microprocessor system with dedicated input–output modules (but there are also dedicated fuzzy microcontrollers they have specific commands to aid some fuzzy inference steps [6]). These systems are cheaper than hardware solutions and more flexible [7].

There are a lot of fuzzy logic inference system various implementations. Some of them uses simplifications of the primary fuzzy logic algorithm. It allow one to create various system architecture. It is not easy, in this case, to compare different solutions of fuzzy systems and a definition of the criteria on the basis of which it can be decided which system is better than another one. In the paper is proposed a fuzzy inference model that can be used to estimate main parameters of the system such as implementation cost (especially in hardware solutions) and time to obtain result.

Fuzzy inference systems usually use a classic Mamdani's fuzzy inference model [2,4]. The inference model can be simplified to improve performance and to reduce software cost of the system. The paper presents simplified Mamdani's inference model and its implementation in the fuzzy logic controller. The controller is based on STM32F4Discovery development board [8] with ARM7 (STM32F407VG [9]) microcontroller. The performance of the proposed controller is compared with another software and hardware solutions of fuzzy logic controllers.

The paper is structured as follow: in Section 2 the main background of Mamdani's fuzzy inference algorithm is presented, classic and simplified models of fuzzy inference systems are discussed in Section 3, general architecture and some implementation issues of the fuzzy logic controllers are described in Section 4. The work is concluded in Section 5.

2. Fuzzy inference system

The K-inputs MISO–FITA (Multiple Inputs Single Output–First Inference Than Aggregate [10]) fuzzy logic inference system (FIS) consists of the following components: a fuzzification module, an inference module, a knowledge base and a defuzzification module (Fig. 1). The first one converts input crisp values $\mathbf{x}' = [x'_1, x'_2, \ldots, x'_K]$ into corresponding fuzzy sets $\mathbf{A}' = [A'_1, A'_2, \ldots, A'_K]$.

The knowledge base describes general behaviour of the system. It consists of two parts: definitions of input and output linguistic variables and a rule base. The rule base is a collection of rules in the form (for rth rule)

$$\text{IF } (X_1 \text{ is } A_{1r}) \text{ AND } \ldots \text{ AND } (X_K \text{ is } A_{Kr}) \text{ THEN } (Y \text{ is } B_r), \quad (1)$$

where $X_1, X_2, \ldots, X_K$ and Y are input and output linguistic variables respectively, $A_{1r}, A_{2r}, \ldots, A_{Kr}, B_r$ are linguistic values described by fuzzy sets [11,12].

The inference module computes output fuzzy set B' for current input values $\mathbf{x}' = [x'_1, x'_2, \ldots, x'_K]$ (converted to fuzzy sets $\mathbf{A}' = [A'_1, A'_2, \ldots, A'_K]$) according to the formula

$$B' = \mathbf{A}' \circ \mathcal{R}, \quad (2)$$

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http://dx.doi.org/10.1016/j.micpro.2015.11.012
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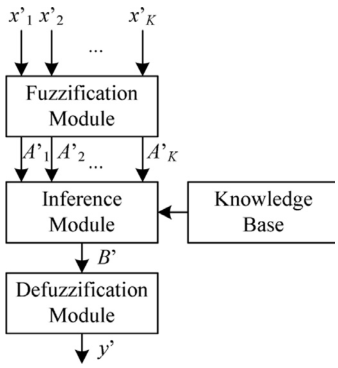

Fig. 1. General architecture of the fuzzy inference system.

where symbol $\circ$ denotes the compositional rule of inference operator (e.g. sup-min or max-min), and $\mathcal{R}$ represents a relation between premise (IF part of the rule) and antecedent (THEN part of the rule) parts of the all aggregated rules, stored in the rule base [10,12]. The relation $\mathcal{R}$ has the general form

$$\mathcal{R} = \mathbf{A} \rightarrow B, \tag{3}$$

where symbol $\rightarrow$ defines a fuzzy implication, $\mathbf{A}$ and B denotes fuzzy sets of the premise and the antecedent part of the rules [10,11].

The defuzzification module converts an output fuzzy set B' into a crisp value y'.

Practical implementation of fuzzy systems uses, in most cases, classic Mamdani's fuzzy inference algorithm [4,11,12]. In this case the main operators in fuzzy logic i.e. sum and product are equal to MAX and MIN operators respectively, the composition (2) is equal to max–min operations and the fuzzy implication operator (3) is equal to MIN operator.

Taking into account, a membership function of an output fuzzy set B' is given by the formula [10,11]

$$\mu_{B'}(y) = \bigvee_r (\tau_r \wedge \mu_{B_r}(y)). \tag{4}$$

where $\bigvee$ denotes an aggregation operator (equal to MAX operator), $\mu_{B_r}(y)$ is a membership function of the fuzzy set of the consequence part of the rth rule B_r (1) and τ_r is the level of activation of the rth rule. The τ_r parameter is given by the formula

$$\tau_r = \bigwedge_{k=1}^{K} [\mu_{A_{kr}}(x'_k)] \tag{5}$$

where $\mu_{A_{kr}}(x'_k)$ is a value of the membership function of the fuzzy set A_{kr} for input value x'_k.

Mamdani's inference method for example fuzzy system with two inputs, one output and two rules is shown in Fig. 2.

Let us consider one of the rules, for example rule (1). Appropriate values τ_{11} and τ_{22} of the membership functions $\mu_{A_{11}}$ and $\mu_{A_{12}}$ are computed for current input values x'_1 and x'_2 (singleton fuzzification method). The activation level of the rule is τ_{22}, according to (5). The output fuzzy set B_1 is truncated on level τ_{22}. These steps are performed for all rules and the partial results are aggregated (using MAX operator) to obtain the final result – fuzzy set B'. Then it is defuzzified to crisp value y', usually using COG method, according to formula

$$y' = \frac{\int \mu_{B'}(y)\, y\, dy}{\int \mu_{B'}(y)\, dy}. \tag{6}$$

A relatively complex calculation in presented algorithm comprise aggregation of partial results as a form of fuzzy sets and defuzzification fuzzy set B'. To improve performance of a fuzzy system, one can convert fuzzy sets of the output linguistic variable Y (e. g. using COG defuzzification method) into appropriate singleton fuzzy sets (zero-order Takagi–Sugeno model) as is shown in Fig. 3.

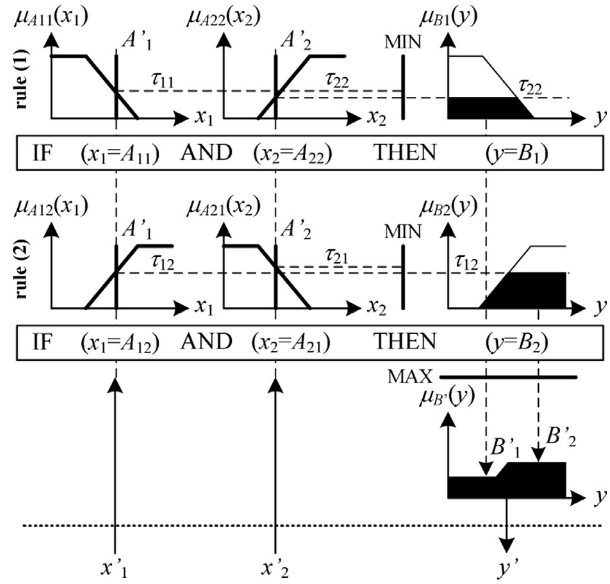

Fig. 2. Mamdani's inference algorithm for example fuzzy system with two inputs and two rules.

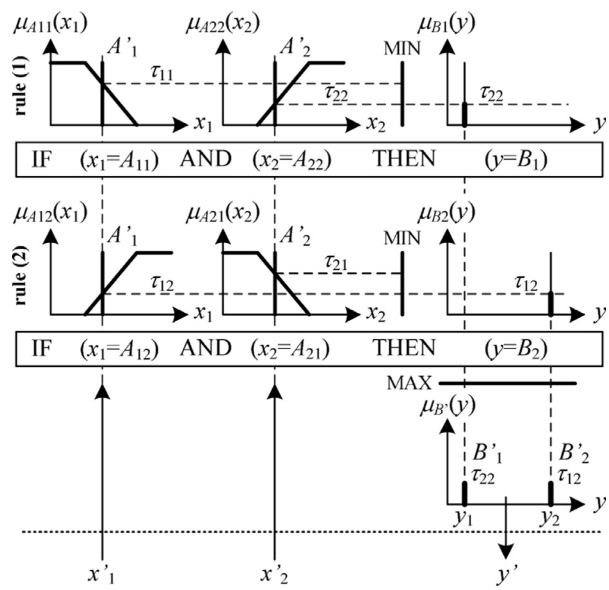

Fig. 3. Mamdani's inference algorithm for example fuzzy system with two-inputs, two-rules and singleton output fuzzy sets.

In this case, the output crisp value y' can be calculated with the simplified formula

$$y' = \frac{y_1 \cdot \tau_{22} + y_2 \cdot \tau_{12}}{\tau_{22} + \tau_{12}}. \tag{7}$$

3. Models of the fuzzy inference system

On the basis of the algorithm, presented in Section 2, has been proposed a model of the fuzzy inference system, as is shown in Fig. 4. For simplification, it has only two inputs, one output and four rules. It consists of A_{ij} $(i, j = 1, 2)$ and B_n $(n = 1, 2)$ modules, two junction matrices J_1 and J_2, AND_1, AND_2 and OR fuzzy gates. The modules A_{ij} and B_n contain membership functions of appropriate linguistic input and output values respectively. The first junction matrix J_1 (with AND_1 fuzzy gates and connections marked as black circle) makes a combination of all the values for all inputs. The connections (marked as