Research on Implementation Method of Fuzzy Logic Control Based on MCU

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Abstract. Fuzzy control belongs to the category of intelligent control, which has outstanding control advantages for more complex systems. Firstly, based on Matlab sltank fuzzy control system, a data extraction model has been established in this paper. By running the model, a number table can be obtained. Secondly, the number table is embedded into the two-dimensional lookup table module, and the C code is generated by real time workshop (RTW) function. Finally, the interpolation principle analysis is carried out, and the interpolation algorithm of two-dimensional lookup table is embedded into the MCU for testing. The real-time test results show that the interpolation result of the MCU is consistent with the off-line simulation result, and the real-time control of the MCU can be guaranteed.

1. Introduction

Fuzzy control is an intelligent control based on fuzzy mathematics. Its essence is to imitate human intelligent decision in the control process and then obtains the precise control effect [6] [10]. Fuzzy control is based on the human experience of the controlled object, so the controller does not need to know the internal structure of the controlled object and its mathematical model. This is very beneficial for the automatic control of complex systems that cannot be automated by traditional control. The MCU has simple structure, high reliability, fast processing speed and strong control function, and is widely used in industrial and automotive electronic control systems [7] [4]. However, the fuzzy logic control algorithm is implemented in the toolbox mode, and its application in MCU is limited [2] [5]. Based on the sltank model in Matlab, this paper extracts the data in the fuzzy controller of sltank, and then generates the automatic code through the RTW function. Finally, the principle of the interpolation algorithm is analyzed, and which is tested by the MCU [8] [5]. The test results show that method in the paper can achieve the purpose of implementing fuzzy control by MCU, and has good engineering application and popularization value.

2. Ease of Use Sltank model and lookup table data extraction

2.1. Sltank model introduction

The existing Sltank model in Matlab is shown in Figure1. The model consists of a PID controller and a fuzzy controller, which can be converted by a constant module and a switch module [3]. Fuzzy logic controller in this Sltank system is established by the fuzzy control box, and the control object is composed of Valve and Water tank modules. The water level of the tank is controlled by adjusting the water valve and the water flow rate. In order to make the simulation image vivid, the animation simulation display module animtank is added to the simulation system, which shows a water bucket in
which the water level follows the fluctuation of the input signal, which can visually see the dynamic situation of the water level change.

![Figure 1: Sltank model](image1)

**Figure 1. Sltank model**

2.2. **Data extraction based on Simulink model**

The fuzzy control algorithm built by the fuzzy logic control toolbox cannot be directly used for the MCU [1]. To implement the fuzzy control algorithm in the MCU, the fuzzy control module established by the toolbox needs to be converted into a data lookup table module, and then embedded into the MCU. Firstly, the data extraction model is established in Matlab/Simulink, and then the M script file is used to compile the algorithm to obtain the input and output data of the fuzzy controller.

1) Establish a data extraction model

The data extraction model established in Simulink is shown in Figure 2. Among them, level and rate are constant modules, Sltank FLC is a fuzzy logic controller, and To Workspace module can store interpolation results into the workspace. The muxl module is between the constant module and the fuzzy controller. The Muxl module takes the water level deviation and the rate of change of the deviation as two components to form a vector input into the fuzzy controller. Sltank FLC is the Fuzzy Logic Controller module in the Sltank model (Figure 1). When different level and rate values are input, there will be corresponding data output, so that the data in the sltank model can be extracted according to the model.

![Figure 2: Data extraction model](image2)

**Figure 2. Data extraction model**

2) Design of M file

In order to obtain the model data in Figure 2, the algorithm is written in the M file, and the algorithm flow chart is shown in Figure 3. The three-dimension curved surface based on obtained data is shown in Figure 4. By comparison, the graph is consistent with the output surface observation window of the Sltank FLC model, thereby verifying the correctness of the obtained data. When extracting model data, the more data is extracted, the higher the accuracy of the output data. However, the storage space of the MCU data memory is small and the storage data is limited, so the data matrix that satisfies the requirements of the MCU should be selected. Therefore, the M file prepared in this paper chooses to extract a 14x14 data matrix.
2.3. Verification of lookup table data

(1) Method of data embedded into 2-D lookup table module

The 2-D lookup table module will need a data matrix with 14×14 dimensions, and the data format is shown in Table 1. The row of Column is represented as the index number and coordinate value of the rate axis. The column of Row is represented as the index number and coordinate value of the level axis. That is, the level and rate axes have 14 coordinate points, respectively, totally of 196 data matrices.

| Break | Column | (1)  | (2)  | (3)  | (4)  | (5)  | …   | (14) |
|-------|--------|------|------|------|------|------|-----|------|
| Row   |        | -0.1 | -0.085 | -0.07 | -0.055 | -0.04 | …   | 0.095 |
| (1)   | -1     |      |       |      |      |      |     |      |
| (2)   | -0.85  |      |       |      |      |      |     |      |
| (3)   | -0.7   |      |       |      |      |      |     |      |
| (4)   | -0.55  |      |       |      |      |      |     |      |
| (5)   | -0.4   |      |       |      |      |      |     |      |
| …     | …      |      |       |      |      |      |     |      |
| (14)  | 0.95   |      |       |      |      |      |     |      |

(2) Verification of 2-D lookup table module
This work mainly includes two links. In the first link, FLC module is replaced by 2-D lookup table and to workspace is replaced by display module. Moreover, the correctness of the output results by changing the value of level and rate. In the second link, the Mux and FLC module in sltank.slx model are replaced by 2-D lookup table module which has been verified in the first link, and then a sltank.slx model is obtained. Sltank_test.slx is used to verify the control effect of 2-D lookup table module. The simulation result of the lookup table module is shown in Figure 5. According to the image comparison, 2-D lookup table module has the same function as the fuzzy control toolbox module, and the control effect meets the design requirements.

Figure 5. Simulation results of 2-D lookup table module

3. RTW automatic code

3.1. Establishment of RTW automatic code model

Figure 6 shows a simulink model in which two input variables are level and rate, respectively, and the output variable is valve.

Figure 6. Simulink model for RTW automatic code

3.2. RTW automatic code generation

RTW is a code generation environment, which can produce optimized, portable and personalized code directly from simulink model. In the model interface of Figure 6, the model parameters are configured, including the following aspects: 1) The type of solver options adopts fixed-step, and solver adopts discrete; 2) The target hardware of the automatic code selects Freescale, and selects the HC(S)12 system and floating data type; 3) The system target file selects ert.tlc format; 4) The option of only generate code needs to be selected. After finishing this work and running generate code function, a series of C code are generated. Then a C code file is obtained, as shown in Figure 7. The wzj_zph_data.c file is a data file, and the data extracted by the model of FIG. 2 is stored, and is called by the 2-D lookup table function. The main function is included in the ert_main.c file, and the function contains a 2-D look-up table interpolation algorithm.
4. Interpolation principle analysis

Based on C code generated, the interpolation algorithm of 2-D lookup table is extracted and the interpolation principle is analyzed. The interpolation principle of 2-D lookup table is shown in Figure 8.

There are 14 coordinate points on the level axis and rate axis, respectively, and each point has two parameter attributes, namely the coordinate value and the index number. For example, in order to analyze conveniently, the parameter properties of the U, V, W, and O points are assumed to be (-0.7, 2), (-0.55, 3), (-0.04, 4), and (-0.025, 5), respectively (Table 1). There are 196 grid points on the 3D surface, and each point also has 2 attributes: the index number of the grid point in the lookup table array, and the z-axis coordinate value corresponding to this index number. The index number of each point on the 3D surface can be calculated from the corresponding index numbers of the level axis and rate axis. For example, if the index number of the point U is 2 and the index number of the point W is 4, the index number of point I is 4×14+2=58, and the corresponding z-axis coordinate value is −0.059.

![Figure 8. The interpolation principle of 2-D lookup table](image)

It is assumed that the horizontal coordinate of the interpolation point H is located in the point X between the points U and V on the level axis, as shown in Figure 8. The ordinate coordinate of the interpolation point H is located in the point Y between the points W and O on the rate axis. The calculation steps of the z-axis coordinate values of the interpolation points are as follows.

(1) The z-axis coordinate value of point I and point L can be found in the lookup table array, and its difference $\Delta lk$ can be calculated. According to the difference, $tj$ can be obtained, and then the z-axis coordinate value $tb$ of point T can be solved, that is,

\begin{align}
\Delta lk &= ic - ia \\
j &= \frac{ab}{ac} \Delta lk \\
tb &= ia + tj
\end{align}

(1)
Similarly, the z-axis coordinate value $ne$ of the N point can be calculated, that is,

$$ne = (md - pf) \frac{ab}{ac} + pf$$  \hspace{1cm} (4)

According to the difference between $ne$ and $tb$, the value of $ns$ can be obtained. According to the proportional coefficient of $yw$ and $ow$, and the value of $ns$, the value of $qr$ can be obtained. The value of $qh$ is the sum value of $qr$ and $tb$, and then $qh$ is the z-axis coordinates of the interpolation point $Q$. The calculation formula are given by

$$ns = ne - tb$$  \hspace{1cm} (5)

$$qh = \frac{yw}{ow} (ne - tb) + tb$$  \hspace{1cm} (6)

5. Implementation method of fuzzy control based on MCU

In order to realize fuzzy control in the MCU, the 2-D lookup table data needs to be embedded into the MCU, and then the interpolation algorithm program is designed according to the binary interpolation principle mentioned above. MCU derivative selected in this paper is Freescale MC9S12XEP100, and the internal bus frequency is set to 16MHz [9]. The specific implementation steps are as follows.

1. Define the table data variables and import the table data into the MCU project file.
2. The table interpolation function is designed according to the principle of dichotomy interpolation, and the function has 7 parameter variables, which are interpolation point coordinate variable, the maximum index value of row and column grid point, data table variable, and so on.
3. Different interpolation points are set in the main program, and then the table interpolation function is called. Finally, the running result of MCU program can be recorded.
4. Compare the operation results of the MCU with the off-line simulation results of the model.

During test, the value of level and rate will be limited in valid range, respectively. For example, when level is 0.55 and rate is 0.058, Figure 9 and Figure 10 are the verification results of RTW model and MCU, respectively.

![Figure 9. Verification results in 2-D lookup table model](image)

![Figure 10. Verification results in MCU](image)

It can be seen from the figure that the two verification results are consistent, namely the interpolation result is 0.426.

It indicates that the fuzzy control Strategy can be achieved by using the 2-D look-up table interpolation algorithm in MCU.
6. Conclusion
In the Matlab/Simulink environment, the fuzzy logic control algorithm is implemented in the toolbox mode, and its application in MCU is limited. For the fuzzy controller with two input and single output types, a 2-D number table can be obtained through the M file programming algorithm, and then the lookup table interpolation algorithm can be obtained by the RTW automatic code function. The interpolation principle is obtained in this paper, and verification test is carried out in MCU. The results show that the MCU calculation results are consistent with the fuzzy control off-line simulation results, and can meet the real-time requirements. Therefore, the implementation method of fuzzy logic control in MCU is feasible.

Acknowledgments
The work is supported by the tackle key problems plan project in science and technology of Henan "Research and Application of Passive Entry & Passive Start Control System for Vehicle" (Item Number: 172102210595).

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