Application of Fuzzy Logic Control for the Time Synchronization

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Abstract: The accurate Time Synchronization requests two clocks which have not only the same frequency but also the same phase. To fulfill this requirement in communication networks, especially for the TD-SCDMA, we could discipline the oscillator with the pulse-per-second (PPS) given by GPS. The conventional PID (proportional integral and derivative) algorithm is generally used to control the output frequency of the oscillator. However, it is too difficult to achieve the synchronization of both the frequency and the phase at the same time. In this case, the Fuzzy Logic can be used to solve this problem. According to the implementation, the controller, a combination of the PD algorithm and the Fuzzy Inference System (FIS), designed in this research is proved to be effective and more efficient than the conventional PID controller.

Keywords: fuzzy logic control; PID control; time synchronization

1. Introduction

The accurate time synchronization is requested in communication networks. As are demanded by the TD-SCDMA [1], the frequency error should be less than 0.05ppm, and the phase error should be less than 3μs. Actually, to satisfy the application in communication networks, the frequency error must be less than 1ns and the phase error must be less than 1μs. Nowadays, the most extensively used reference time in communication fields is provided by the GPS [2], because the GPS time could ensure long term stability. Moreover, a high precision oven-controlled crystal oscillator (OCXO) is necessary for the time accuracy.

To combine the advantages of the excellent short-term stability of high quality oscillator with the advantages of GPS signals over the long term, Wang [3] proposed to use a direct digital synthesizer (DDS) to generate the desired frequency. Since the DDS is far from being an ideal source, its noise floor and spurs will be transferred to the output and amplified. He suggested mixing the DDS output with an ultra stable oscillator (USO) output to make a DDS-driven phase-locked loop (PLL) to overcome this limit. Because his study is applied for the Distributed Synthetic Aperture Radar, which has a strong military background, the standard and cost of the USO are higher than the commercial product. As a result, we prefer to synchronize the local time with the GPS time by adjusting OCXO's input voltage directly, for the reason that this scheme can reduce the cost of the oscillator and be applied more easily and extensively.

In this paper, a Fuzzy Logic Controller is introduced to realize the time synchronization. This controller comprises of two parts—a PD controller and a FIS [4,5]. The PD controller tunes the frequency, while the FIS adjusts the phase as well as the frequency. The Takagi-Sugeno [6] (T-S) fuzzy if-then rules, which have been used widely in both modeling and control, are chosen to make the kernel of the FIS.

This paper is organized as follows: Section 2 gives a brief introduction to the FIS and its comparison with PID algorithm; the structure and design of the controller is studied in Section 3; in Section 4, the implementation is displayed and the effectiveness of the controller is demonstrated; at last, the conclusion would be drawn as the Section 5.

2. FIS and PID

2.1 Structure of FIS

The FIS usually has five function blocks [7]:

1) A fuzzification interface which transforms the crisp inputs into degrees of math with linguistic labels.

2) A rule base which containing a number of fuzzy if-then rules.

3) A data base which defines the membership functions of the fuzzy sets.

4) A decision making unit which performs the fuzzy inference on the rules.

5) A defuzzification Interface transforms the fuzzy results of the inference into a crisp output.

The rule base, data base and decision making unit are supposed to work together to fulfill the fuzzy reasoning.

2.2 T-S Fuzzy If-Then Rule

A fuzzy if-then rule often has two parts: premise part and consequent part. The T-S fuzzy if-then rule proposed by Takagi and Sugeno has fuzzy sets involved only in the premise part. For example, by using two T-S fuzzy if-

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then rules, a system with two inputs and one output can be described as follows:

If x is A_1, and y is B_1, then $\Delta u_1 = f_1(x, y)$ (1)

If x is A_2, and y is B_2, then $\Delta u_2 = f_2(x, y)$ (2)

Where A_i and B_i ($i = 2$) in the premise part are linguistic labels which are characterized by appropriate membership functions. x, y are the input variables, and Δu_i is the output, which corresponds to each rule.

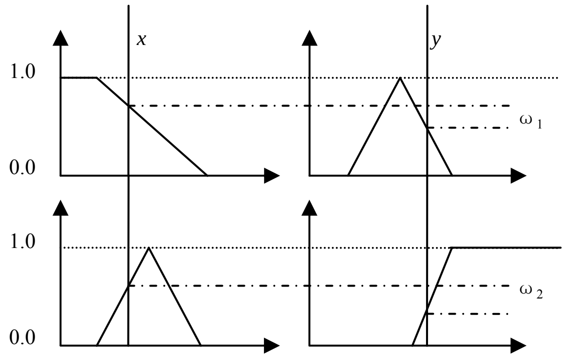

Figure 1. Fuzzification and fuzzy reasoning

After the process of fuzzification and fuzzy reasoning, which is illustrated by Figure 1, the final crisp output will be generated as:

$$\Delta u = \frac{\omega_1 \times \Delta u_1 + \omega_2 \times \Delta u_2}{\omega_1 + \omega_2} \tag{3}$$

ω_1 and ω_2, which are the weight of (1) and (2), can be generated by multiply the membership values of x and y (or just choose the minimum one).

Compared to general fuzzy-if rule, the advantage of the T-S fuzzy if-then rule is the consequent part which can be described by a non-fuzzy equation. This makes it much easier to use in controlling.

2.3 The Comparison between FIS and PID

In this research, the PID algorithm has the following defects:

1) First, as the V-F relation is linear approximately, the conventional PID controller could not get a stable synchronized frequency without carefully tuned parameters which request a lot of experiments.

2) Besides, after the frequency gets stable, it is difficult to synchronize the phase quickly without losing synchronization of frequency for PID controller.

3) Even though, there are still lots of uncertainties (e.g., aging of the oscillator and temperature influence), which could affect the frequency. And PID controller could not deal with these potential factors.

By contrast, a fuzzy inference system containing fuzzy if-then rules can model the qualitative aspects of human knowledge and reasoning processes without employing precise quantitative analyses. So compared to the PID control, the fuzzy logic control has following advantages:

1) The fuzzy logic control is suitable for non-linear controlling, so the nonlinear V-F relation will not be a problem anymore.

2) As the phase and the frequency are both input variables in the premise part, their influence could be adjusted by the corresponding membership values, and limited by the parameters. Hence it can balance this conflict much easier.

3) Since this system uses the OCXO, which is less sensitive to temperature than normal oscillators, we do not need to add the temperature related rules. But the fuzzy control supports dealing with other factors by adding new rules.

3. The Designing of the Controller

3.1 Structure of the Controller

In this paper, the controller contains a PD controller and a FIS. This combination deserves a switch of the control algorithm after the frequency gets into a certain range. The PD controller is supposed to reduce the frequency error under a certain limit which is 10ns in this research. Then the FIS should be activated. The structure of the controller is illustrated in Figure 2.

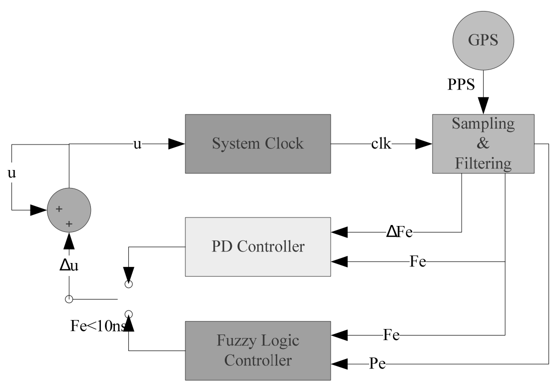

Figure 2. Structure of the controller

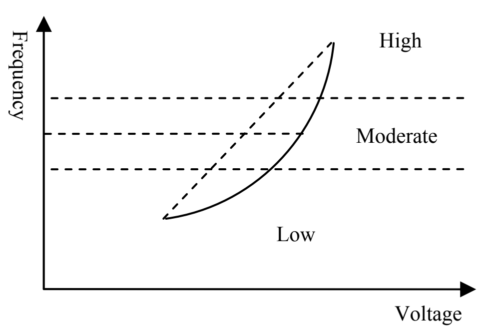

Figure 3. Assumed F-V relation

P_e is the phase error, F_e is the frequency error, Δu is the adjustment of the control voltage. Since P_e might be too large for the FIS to adjust, the phase will be synchronized forcibly with the GPS time when F_e satisfies the limit for the first time.

3.2 The Designing of the FIS

In this system, the V-F relation is not strictly linear, so it cannot be described by one linear function aptly. Based on testing results, the V-F relation near the desired frequency should be assumed as a concave curve expressed by Figure 3.

As is illustrated by Figure 3, the frequency can be described by three fuzzy sets: *low*, *Mod* (Moderate) and *high*. We could use five or more fuzzy sets, but this will engage too much rules to keep the FIS efficient. Those three fuzzy sets are not strictly separated by the dotted line displayed in Figure 3. Instead, they have intersections (see Figure 4) which help the FIS working better by active different rules at the same time.

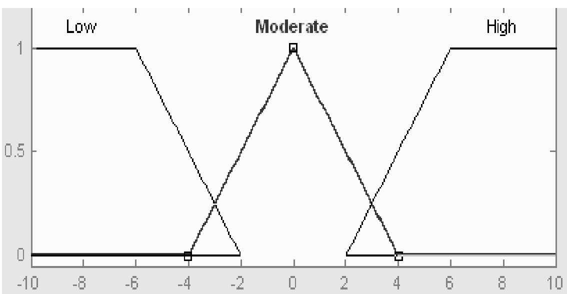

Figure 4. Membership function of frequency

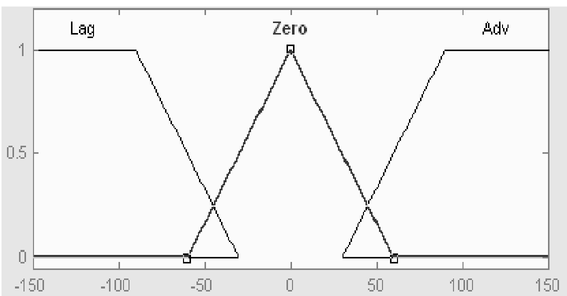

Figure 5. Membership function of phase

Similarly, the situation of the phase should also be divided into three classes (as Figure 5 displayed): *lag*, *zero* and *advance*. But the *lag* and the *advance* are symmetrical; therefore two fuzzy sets (*nonzero* and *zero*) could be enough to descript it.

Considering that variation of the frequency could also influence the phase, we introduce three frequency sets and two phase sets to make the rule base. As a result, at least six rules should be involved. These rules can be described as follows:

1) If phase is *nonzero* and frequency is *low*, then

$$\Delta u_1 = a_1 \times P_e + b_1 \times F_e \tag{4}$$

2) If phase is *nonzero* and frequency is *Mod*, then

$$\Delta u_2 = a_2 \times P_e + b_2 \times F_e \tag{5}$$

3) If phase is *nonzero* and frequency is *high*, then

$$\Delta u_3 = a_3 \times P_e + b_3 \times F_e \tag{6}$$

4) If phase is *zero* and frequency is *low*, then

$$\Delta u_4 = a_4 \times P_e + b_4 \times F_e \tag{7}$$

5) If phase is *zero* and frequency is *Mod*, then

$$\Delta u_5 = a_5 \times P_e + b_5 \times F_e \tag{8}$$

6) If phase is *zero* and frequency is *high*, then

$$\Delta u_6 = a_6 \times P_e + b_6 \times F_e \tag{9}$$

Parameters a_i and b_i ($i = 1,2,3,4,5,6$) should be tuned for different rules based on a value calculated by the relationship of the voltage and the frequency.

There are three steps of the fuzzy inference process: fuzzification, fuzzy reasoning, and defuzzification. The details can be described as follows:

1) Fuzzification: two inputs (P_e and F_e) are compared with the membership functions (illustrated by Fig. 4 and Figure 5) on the premise part to obtain the membership values of each linguistic label.

2) Fuzzy reasoning: the membership values on premise part are combined to get the weight of each rule. Here, the weight ω_i ($i = 1,2,3,4,5,6$) can be expressed as:

$$\omega_1 = zero(P_e)^c * low(F_e) \tag{10}$$

$$\omega_2 = zero(P_e)^c * Mod(F_e) \tag{11}$$

$$\omega_3 = zero(P_e)^c * high(F_e) \tag{12}$$

$$\omega_4 = zero(P_e) * low(F_e) \tag{13}$$

$$\omega_5 = zero(P_e) * Mod(F_e) \tag{14}$$

$$\omega_6 = zero(P_e) * high(F_e) \tag{15}$$

After calculating the weight, generate the qualified consequent of each rule, as (4)-(9) showed before.

3) Defuzzification: the consequents are aggregated by using the weight get from (10)-(15) to get a crisp output.

The weighted average scheme is chosen to complete the defuzzification in this paper as it is not very complicated, and the output is:

$$\Delta u = \frac{\sum_{i=1}^{6} \omega_i \times \Delta u_i}{\sum_{i=1}^{6} \omega_i} \tag{16}$$

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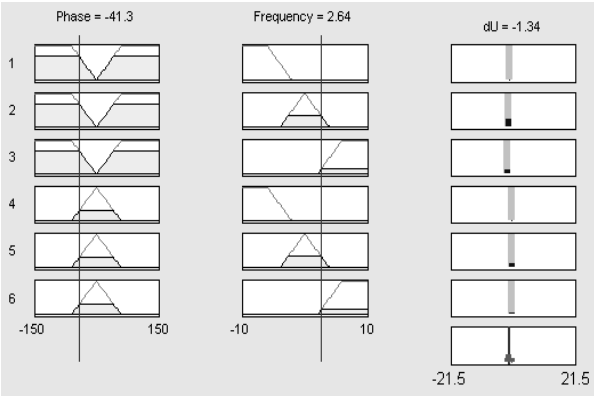

Figure 6. Fuzzy inference view

Figure 6 gives a vivid example of this fuzzy inference process with given inputs. In this situation, the frequency is between *high* and *Mod* , and the phase between *zero* and *lag* , so rule 2, 3, 5, and 6 are activated at the same time. Then by using the defuzzification interface, the FIS will get a better result.

4. Implementation

The experiment is implemented with a test board of the TD-SCDMA NodeB. The structure of the time synchronization model can be illustrated by Figure 7.

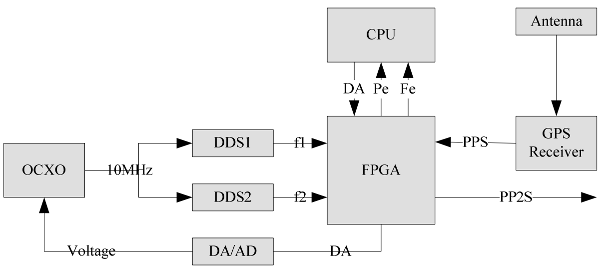

Figure 7. Time synchronization model

According to the results of the implementation, performance of the fuzzy logic controller is proved to be more effective and more reliable than the PID controller.

Table 1. Comparison of PID and fuzzy control

Algorithm	PID	FUZZY
Average Synchronizing Time	15min	4.5min
Longest Synchronizing Time	20min	6min
Resynchronization Time	>5min	<3min
Average Phase Stability	± 60ns	± 30ns
Worst Phase Error	>300ns	<150ns
Lost Synchronization (in 72 hours)	once	none

Notice: the average data in this table comes from 10 tests. The Resynchronization Time is tested by removing the GPS receiver for several minutes. Unfortunately, due to the limitation of the space, there is nowhere to show all of the testing results.

5. Conclusions

In this paper, the Fuzzy Logic is introduced to design and develop a controller to solve the Time Synchronization problem. Considering that the Voltage versus Frequency relation is linearized approximately in overall situation, we combine the PD algorithm with the FIS to make a fuzzy controller. And the experimental implementation demonstrates the effectiveness and reliability of this mixed fuzzy controller.

Other investigations on this thesis include the request of effective methods to tune the membership functions and the fuzzy rules, the lack of standard methods for transforming human knowledge or experience into the rule base and data base of a fuzzy inference system, and so on. Nowadays, there are a lot of research works on Artificial Neural Networks (ANN), Genetic Algorithm (GA), etc. To combine the FIS with ANN [7] or GA, there might be some new adaptive controllers, which could perform better and designed easier.

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