AUTOMATIC FREQUENCY CALIBRATION USING FUZZY LOGIC CONTROLLER

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Abstract

A way of frequency calibration using fuzzy logic controller (FLC) is presented in this paper. Generally, atomic clocks tend to drift due to temperature, aging, or some environmental effects. It is sure that one cannot compensate for the drift with a fixed amount of control quantity. As a controller, it has the task to adaptively catch up with the variation. Our approach takes advantage of FLC to determine the control quantity. Three procedures are employed in our approach. Firstly the performance of the device being calibrated is observed continuously. Then the FLC uses the performance data to generate the control quantity. Finally the FLC calibrates the device using the computed control quantity. The FLC can calibrate the device at any time since the performance of the device is continuously being monitored. In the experiment, we use FMAS (Frequency Measurement and Analysis System) as the performance evaluation equipment and the FLC is realized by a PC. In the experiment, a cesium-beam oscillator is chosen as the target. The result validates the effectiveness of our approach. An oscillator with frequency offset of -1.4×10^{-13} *can be improved to approximately* -1.0×10^{-14} *after one week of calibration.*

INTRODUCTION

Due to temperature, aging, or some environmental effects, atomic clocks generally tend to drift in an unknown way. This ends up with a difficulty in characterizing the clock. For example, it is not possible to compensate for the drift with a fixed amount of control quantity during frequency calibration [1]. A fuzzy logic controller (FLC) has been deemed to be suitable for use in a time-varying, nonlinear, or hard-to-defined system [2]. In this paper, we use FLC to adaptively determine the control quantity to compensate for the drift.

Three procedures are employed in our approach. First, the performance of the device being calibrated is continuously being monitored. Note that this requires a reference frequency with accuracy much better than that of the device being calibrated. Second, the performance data are connected to the FLC. Upon receiving data from the performance evaluation equipment, the FLC calculates the control quantity according to some fuzzy rules. Finally, the FLC calibrates the device through the command compliant to some particular form. The FLC can calibrate the device according to some predefined criteria. For example, it can be done at a regular interval or on an on-demand basis.

The performance evaluation equipment used in this work is the FMAS (Frequency Measurement and Analysis System), measurement equipment developed by NIST (National Institute of Standards and Technology). The FLC is realized by a commercial PC. Fig. 1 shows the system configuration. The reference frequency used is the master clock in our laboratory. The accuracy of the reference frequency is better than 5×10^{-14} and hence is sufficient for calibrating most commercial oscillators.

Let $y_{ref-ideal}$ denote the frequency offset of the reference frequency relative to the ideal frequency; i.e., $y_{ref-ideal} = (f_{ref} - f_{ideal}) / f_{ideal}$. Similarly, the frequency offset of the user's clock relative to the reference frequency is $y_{usr-ref} = (f_{usr} - f_{ref}) / f_{ref}$ and that of the user's clock relative to the ideal clock is $y_{usr-ideal} = (f_{usr} - f_{ideal}) / f_{ideal}$. Having these relations, the frequency offset of the user's clock relative to the ideal clock can be expressed as

$$y_{usr-ideal} = y_{ref-ideal} + \frac{f_{ref}}{f_{ideal}} y_{usr-ref} \tag{1}$$

Hence, if $f_{ref} \cong f_{ideal}$, then $y_{usr-ideal}$ can be approximated by

$$y_{usr-ideal} \cong y_{ref-ideal} + y_{usr-ref} \tag{2}$$

It is obvious from (2) that $y_{usr-ref} \cong y_{usr-ideal}$ provided $y_{ref-ideal} << y_{usr-ref}$. This means that the frequency offset measured from the user's clock can be treated as that relative to the ideal frequency provided that the reference clock is good enough.

To verify the effectiveness of the proposed method, we choose a cesium-beam oscillator with accuracy of -1.4×10^{-13} as the device being calibrated. Experiment result shows that the accuracy can be improved to approximately -1.0×10^{-14} after one week of calibration.

We have assumed in this paper that the reference frequency is available in the site where calibration is performed. If this is not the case, the techniques of transfer standards or means by which oscillators can be made traceable to some standards must be used. Examples of these are via LORAN-C, GPS, common-view GPS, or the technique of GPS carrier phase.

SYSTEM DESCRIPTION

For convenience in later description, the following symbols are defined: y denotes the frequency offset, Δe denotes the phase offset resulting from the frequency offset at the corresponding interval, φ denotes the control quantity to be applied to the device being calibrated, and the subscript denotes the time index. Note that $\Delta e = yT$ where T is the length of the observation interval. Fig. 2 illustrates the basic idea by which our approach is made possible. In the figure shown, a positive frequency offset is assumed initially, i.e., $y_{n-1} > 0$, and the phase offset at the beginning of each observation interval is assumed to be zero. Note that this is tantamount to balancing the phase offset with an action of single step made at the beginning of each observation interval. Also, we use bold lines to indicate the residual frequency offsets in the corresponding observation interval.

It is intuitively seen that the phase offset resulting from the frequency offset of $y_{n-1} > 0$ (i.e., Δe_{n-1} as shown in the figure) can be balanced by imposing a phase offset with direction opposite to the former; i.e., $\varphi_n = -\Delta e_{n-1}$. However, as mentioned in the last section, oscillators tend to drift in an unknown way. It is therefore not possible to keep residual frequency offset to a minimum with such a fixed amount of control quantity. If the residual is equal to zero (i.e., $y_n = 0$) after the above action is done, then the control quantity is deemed to be temporarily correct. In this case, the controller has the task to keep the same control quantity in the next observation interval; i.e., $\varphi_{n+1} = \varphi_n$ as shown in Fig. 2a. If the residual has a positive slope, i.e., $y_n > 0$, then the controller has the task to increase the controller quantity; i.e., $|\varphi_{n+1}| > |\varphi_n|$ as shown in Fig. 2b. On the contrary, if the residual has a negative slope, i.e., $y_n < 0$, the controller has the task to decrease the control quantity; i.e., $|\varphi_{n+1}| < |\varphi_n|$ as shown in Fig. 2c.

The variation of phase error is generally nonlinear. The one shown in Fig. 2a is but a hypothetical case. It cannot be an easy job to have a proper control quantity for atomic clocks. To overcome this difficulty, the FLC is used to evaluate the control quantity before applying it to the device being calibrated. In this work, the control quantity is made to be adaptive in the way

$$\varphi_{n+1} = \varphi_n + \Delta\varphi_n \tag{3}$$

where $\Delta\varphi_n$ is the updating term and is determined by the FLC. The initial value of φ_n can be chosen arbitrarily.

Fig. 3 shows the basic structure of an FLC. It consists of the following four units: 1) fuzzification unit, 2) fuzzy reasoning unit, 3) fuzzy rule base and fuzzy data base unit, and 4) defuzzification unit. Two variables are used as the input to the fuzzy rule base. One is the frequency offset read from the FMAS (i.e., y_n). The other is the difference of the frequency offsets between two adjacent observation intervals (i.e., $\Delta y_n = y_n - y_{n-1}$). Table 1 gives the fuzzy rule base used in this work. The ranges for the two input variables and the output are divided into five parts. They consist of the following fuzzy sets: NB (Negative Big), NS (Negative Small), ZE (ZEro), PS (Positive Small), and PB (Positive Big). The membership functions chosen for these fuzzy sets are of a triangular form. Fig. 4 shows the membership functions stored in the fuzzy data base. Additionally, the fuzzy reasoning method chosen is the Max-Min method, and the mean of maximum (i.e., modified centroidal) is used as the method of defuzzification [2].

EXPERIMENT RESULTS

In our experiment, a cesium-beam oscillator is chosen as the device being calibrated. The frequency offset of a cesium lies between $y_n \in [-1\times10^{-12},\ 1\times10^{-12}]$ and therefore $\Delta y_n \in [-2\times10^{-12},\ 2\times10^{-12}]$. Taking these ranges into account, the membership functions shown in Fig. 4 are scaled by 10^{-13} and 2×10^{-13} respectively for y_n and Δy_n. The range for the output is the same as y_n.

The oscillator originally has frequency offset of -1.4×10^{-13}. The result shows that the frequency offset can be improved to -1.0×10^{-14} after about one week. Fig. 5 shows the variation of the frequency offset.

CONCLUSIONS

A way of adaptive frequency calibration using a fuzzy logic controller is presented in this work. Atomic clocks tend to drift due to aging or some environmental effects and generally leads to irregular variation in characteristics. Our approach takes advantage of fuzzy logic controller (FLC) to determine the control quantity adaptively. Experiment results validate the effectiveness of our approach.

REFERENCES

[1] M.A. Lombardi, *Tutorial on frequency calibrations and time transfer*, NIST Time and Frequency Division, Colorado, USA.

[2] J. Yan, M. Ryan, and J. Power, *Using fuzzy logic*, Prentice Hall International (UK) Limited 1994.

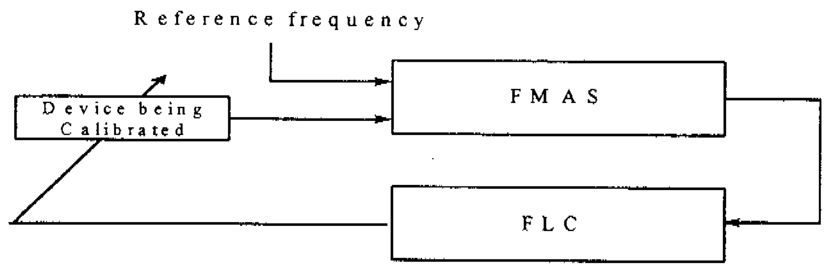

Fig. 1 The proposed frequency calibration method.

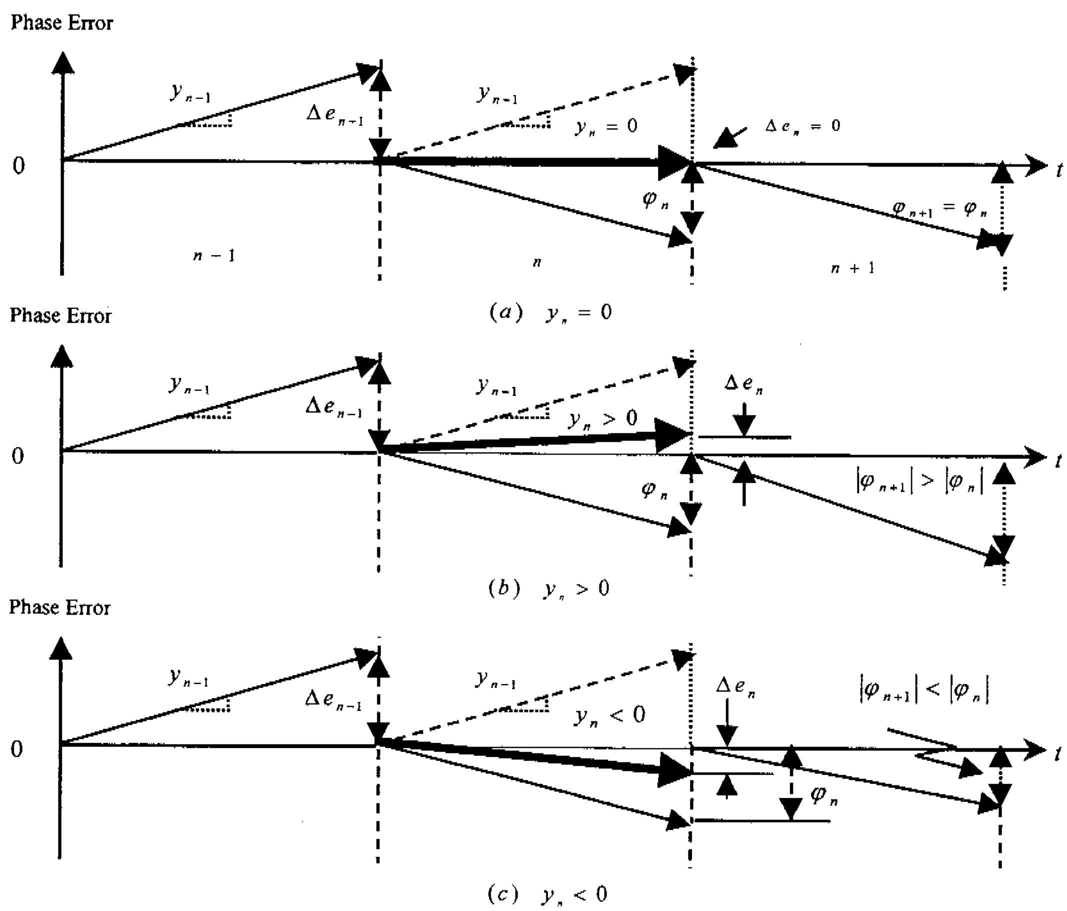

Fig. 2 Basic idea for frequency calibration: (a) $y_n = 0$, (b) $y_n > 0$, and (c) $y_n < 0$.

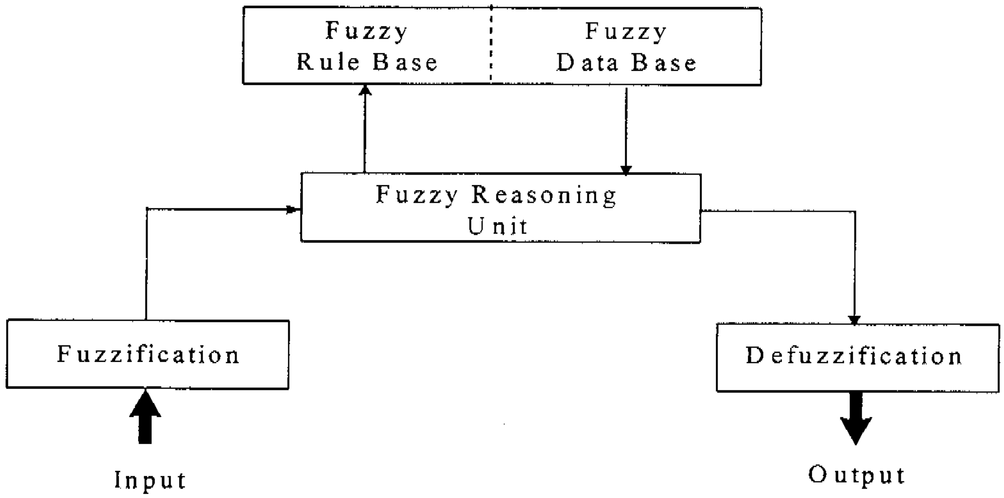

Fig. 3 Basic structure of fuzzy logic controller.

Table 1 Fuzzy rule base.

y_n / Δy_n	NB	NS	ZE	PS	PB
NB	PB	PS	ZE	PS	NB
NS	PB	PS	ZE	PS	NB
ZE	PB	ZE	ZE	ZE	NB
PS	PB	NS	ZE	NS	NB
PB	PB	NS	ZE	NS	NB

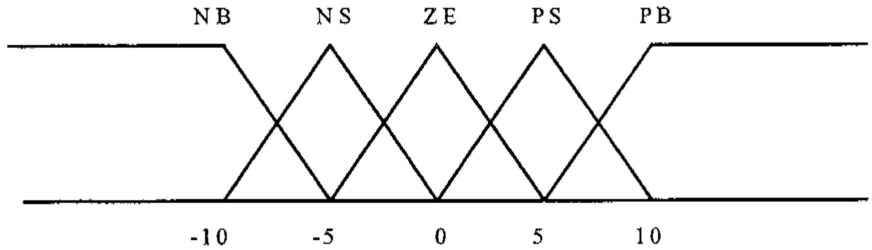

Fig. 4 Membership functions for y_n, Δy_n, and the output.

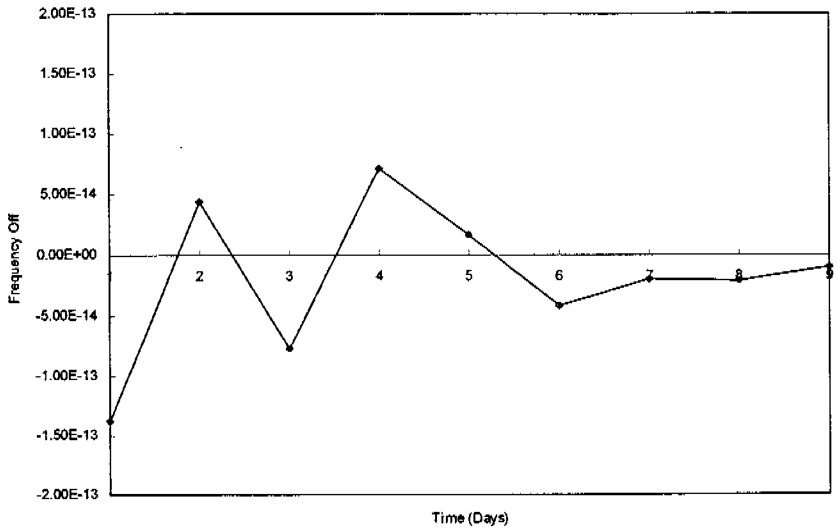

Fig. 5 Frequency offset vs. time.