"Smart Clock: A New Time"

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Smart Clock: A New Time

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Abstract—**The Smart Clock, a pending patent of NIST, opens up the possibility for any clock to be automatically synchronized to an external standard with a minimum of measurements. The concept covers a range of applications from wrist watches and household clocks to the specialized world of high-accuracy clocks. The Smart Clock enhances the accuracy or stability of a clock or oscillator by characterizing it against an external standard. The Smart Clock algorithm uses optimal estimation and prediction to apply a correction to the output of the oscillator, maintaining any combination of time or frequency accuracy or stability within specified limits. The algorithm decides when external measurements are necessary to maintain the desired accuracy or stability. We present here a tutorial description of the Smart Clock system and an example of how it could be used to maintain a simple clock to 1 s using measurements over the telephone lines.**

I. INTRODUCTION

THE Smart Clock concept [1] promises to improve the accuracy or the stability of a clock or oscillator while minimizing the number of calibrations against an external standard. The Smart Clock concept can be realized with a system consisting of the following components: 1) an oscillator, such as a quartz crystal oscillator, 2) a counter for keeping track of the number of oscillations in order to generate time, 3) a microprocessor or computer running the Smart Clock algorithm, 4) a comparison system for measurements against the external standard, and 5) a system for providing the correct time and rate within specified limits. The microprocessor, running the Smart Clock algorithm, initiates measurements of the clock's time offset from an external reference, using the comparison system. The Smart Clock algorithm then uses these measurements to characterize the performance of the oscillator. The system uses this characterization to estimate optimal corrections to the time and/or frequency which are output to some device, and to schedule the next external comparison. The ability of the system to correct its time or frequency improves as more external comparisons are completed, and this in turn allows the interval between the comparisons to be lengthened or the accuracy of the device to be improved. The limits on such improvements depend on the predictability of the oscillator within the Smart Clock's model and the comparison measurement noise. The accuracy of the time or of the frequency (rate offset) of the clock can be maintained within predefined limits, consistent with clock capabilities.

The Smart Clock concept is quite general and has a large range of useful realizations. The oscillator in the Smart Clock system can vary from the common and inexpensive, such as a quartz crystal from an inexpensive wrist watch, to the specialized precision of a hydrogen maser. The external reference can be any time standard, such as the UTC(NIST) primary time scale. The device may be measured against the external time reference using a variety of comparison and communication techniques depending on the application. If the Smart Clock system were referencing a standard nearby, the comparison system might be through the use of cables connected to a time interval measurement system. Examples of other systems include: automated telephone time services, radio or satellite transmissions, and synchronization codes transmitted through the power lines in a home or through the use of infrared diodes. The example system we explore in detail promises to maintain a 1 s accuracy using an inexpensive quartz crystal oscillator. The external reference in this example is the U.S. time standard at NIST, available automatically over the telephone lines using the Automated Computer Time Service (ACTS) [2], [3].

II. OPTIMAL ESTIMATION AND PREDICTION OF A CLOCK

It is well known that the times of any two independent clocks, once synchronized, will "walk away" from one another, and the difference between them will exceed any limit given that the clocks continue to run for enough elapsed time [4], [5]. Improvements in the performance of clocks may slow this process but will never eliminate it. One method for maintaining agreement between two clocks involves a continuous or nearly continuous communication between them. This can be inconvenient and impractical. Often clocks are periodically reset against an external reference to maintain synchronism. Although the two clocks agree within the measurement noise each time the reset is performed, the clock times walk away from one another between resets. Some systems attempt to correct for this using an estimate of the clock rate difference. Any such method of either periodic clock resets or the use of fixed rate offsets is less efficient than it could be if it does not use optimal estimation techniques.

Another common problem is in changing the rate, or "steering" a clock. Some systems steer a clock using a method that itself perturbs the clock's performance, such as varactor control of a quartz crystal resonator. This interferes with the ability to properly characterize that clock.

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The Smart Clock system attempts to avoid these pitfalls. It uses optimal estimation to characterize and predict the offset of its local clock from an external standard, then to steer the output of the Smart Clock system to increase its accuracy or stability in a way that does not destroy the validity of the characterization.

The time offset of one clock from another over a given time interval of length τ can be modeled with both deterministic and stochastic, or random, parameters [4]–[8]. A deterministic system is one which can be predicted exactly for all time, given initial conditions. The deterministic parameters in our clock model are the initial error x_0 of synchronization, an average clock rate or frequency offset y, over the interval, and a drift of frequency, D. These are some components of the model that are deterministic; that is, they are not functions of random variables.

In addition, many variations in the time between two clocks can be modeled in terms of random variables [4]. Fig. 1 shows the residuals in the time offset of a clock based on a quartz crystal oscillator after removing a frequency drift, an average frequency, and a mean time offset. Typically, such fluctuations can arise from coupling of a clock to its environment or from aging. Environmental perturbations such as fluctuations in temperature, pressure, or humidity, can never be completely compensated for. However, if the effects of the environment on a clock are known, they can be incorporated in the model using environmental measurements, thus improving the estimates. The system could also learn an environmental effect adaptively, by measuring a parameter and correlating it with the measurement of the clock against the external reference.

There will always be residual errors that appear random after all other known effects are removed. There are different types of random fluctuations, often called noise types. The most common noise types found in clocks and oscillators are white, flicker, and random walk noise. A noise type can be described in terms of its power spectrum, that is, in terms of the power at different frequencies of a clock's fluctuations. White noise has a flat spectrum from a low-frequency to a high-frequency cutoff. A sound, for example, is white noise if the intensity of low frequencies is the same as that of high frequencies over the audible range. White light is composed of all colors with equal intensity over the optical range. Just as sound and light can be broken down into their component frequencies, any signal can be decomposed in terms of the frequency distribution of its fluctuations. The use of the word ''frequency'' here can be confusing, since its meaning is quite different than when we talk of the frequency, or rate, offset of a clock. The frequency of a fluctuation is often called a ''Fourier frequency,'' after the famous 19th century French mathematician, and is the independent variable of the power spectral density of a signal.

Let us consider random walk fluctuations. Suppose a man starts at a point on an east–west street and flips a fair coin at each step to decide in which direction to take the next step. If it comes up heads he takes a step of fixed size east; if tails he takes a similar step west. If the probabilities of heads and tails are equal, the sequence of heads and tails can be understood as a white noise sequence. That is, if the man started over from the initial point with each step, his fluctuations about that point, either one step east or west at any time, would exhibit white noise. But if the man continues with each step from where the last left off, his motion will be a random walk away from the initial point. His position after N steps will be the sum of all previous steps. We can predict his expected distance from the initial point. After N steps, on the average he will be $\sqrt{N}$ steps away from his initial position [9].

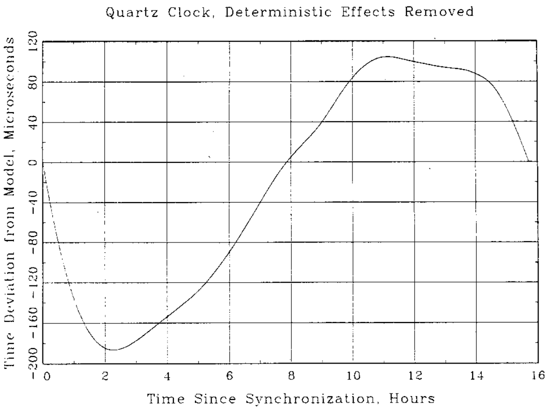

Fig. 1. The residuals in the time offset of a clock based on a quartz crystal oscillator after removing a frequency drift, an average frequency, and an initial time offset.

A random walk process is an accumulation of white noise steps. That is, it is the integral of a white noise process. There is a relationship between fluctuations in the time offset of a clock from a standard, and fluctuations in its frequency or rate offset. In the same way that random walk is the integral of white noise, the time offset of a clock after an interval is the integral of its average rate or frequency offset over that interval. For this reason, white noise fluctuations in the rate offset of a clock will produce a random walk in time.

Flicker noise lies between white and random walk noise, in the sense that a flicker noise process will walk away slower from the initial point than the random walk. While a white noise signal fluctuates around a mean value, a flicker noise signal has no mean value, but, like random walk, will move away from any point without bound. That is, if a signal characterized by either random walk or flicker noise has a value at an initial time, it will eventually exceed any distance away from that value given that it continues for enough time.

We saw that white noise fluctuations in the rate or frequency of an oscillator result in a random walk of the time of a clock based on that frequency. Random walk fluctuations in frequency produce deviations in the time of a clock derived from that frequency. These time deviations are an accumulation or integral of a random walk process. Such a process is sometimes called a random run, since the time walks off much faster than if driven by a random walk process. We often find flicker noise fluctuations in the rate of a clock. Any given clock can have a sum of different random variations, with differing levels of intensity.

The random deviations of typical quartz crystal oscillators are usually characterized [4] by flicker noise in the clock rate or frequency and often also by a random walk in frequency. Previous work has shown that both the flicker and the random-walk frequency fluctuations can be modeled to optimize a digital servo algorithm for the continuous correction of a clock based on a quartz crystal oscillator [10], [11].

III. An Example

We will discuss an example of a Smart Clock system for a simple clock: a display for reading time driven by a quartz crystal oscillator, using a modem to access UTC(NIST) across the telephone lines. We characterize the performance of a 32-kHz quartz oscillator for 16 h, and use this to predict time deviation. We also look at once-per-day measurements of three inexpensive wrist watches over 145 d. Our analysis predicts the ability to maintain under a 1 s accuracy with a 15 s telephone call about once per month, using the existing ACTS of NIST.

As we noted before, Fig. 1 shows the time error residuals of a clock based on a quartz crystal oscillator over a 16 h period after removing the deterministic model: a frequency drift, an average frequency, and an initial time offset. From our characterization of both the deterministic and random parameters we predict what the time error would be up to a month after synchronizing this clock. This is shown in Fig. 2, along with a 2-ms measurement noise level for the ACTS system. The slope of the predicted time error on this log–log plot indicates the noise type driving the error. Initially the time fluctuations are driven by flicker noise variations in time, causing the flat slope in time dispersion from 2–40 s since synchronization. From 40 s, $4.6 \cdot 10^{-4}$ d, to about 4000 s, 0.04 d, the slope of the time dispersion is about +2, meaning the dispersion increases as the square of the time. This is usually due to an unmodeled drift of frequency. Since we have removed an overall frequency drift from the data, this implies that the drift is not constant. After this, from 1 h to about 4 h we find a slope of +3/2 on our log–log plot. This represents random walk variations in frequency; we expect the dispersion of the clock to grow as time to the 3/2 power. We do not know if the random walk process will dominate out to 30 d or whether the drift in frequency of the quartz oscillator will change from our modeled value. If drift dominates, we need to measure our clock offset after 10 d to maintain 1 s accuracy. If the random walk of frequency dominates, we can wait over 1 month to call again. In practice, we would gradually lengthen the time between synchronizations until the behavior of the oscillator for periods out to 1 month or more is characterized.

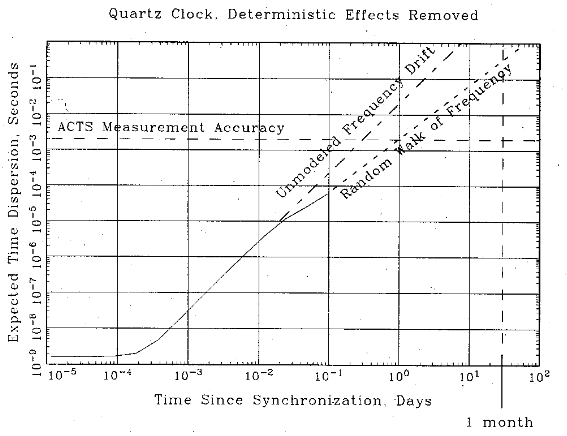

Fig. 2. The predicted time error up to a month after synchronizing the clock of Fig. 1,. along with a 2-ms measurement noise level for the ACTS system.

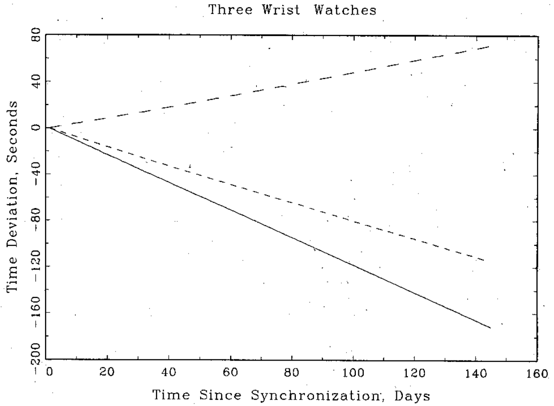

Fig. 3. The time dispersion of three inexpensive wrist watches against UTC(NIST) over a 145-d period.

Fig. 3 shows the time dispersion of three inexpensive wrist watches against UTC(NIST) over a 145 d period. The measurements look like straight lines since the clock errors are dominated by their frequency offsets. Fig. 4 shows the residuals of these respective clocks after removing an estimate of frequency drift, frequency offset, and a mean time from each of them. The peak-to-peak variation in all three over this period is under 1 s. The residuals also show similar structures in all three. We may surmise that these are due to a common environmental perturbation such as temperature. These data suggest that, with a good characterization, one could maintain 1 s accuracy for a month. Also more improvement could be possible through characterizing environmental coefficients.

The ACTS is a system capable of providing time accurate to about 1 ms to any computer over the commercial telephone lines [2], [3], [12]. The computer needs only a modem and some software. It can also work with only a modem and some simple hardware to provide a 1 pulse-per-second (pps) signal within about 1 ms of UTC(NIST) during the telephone call. ACTS provides various infor-

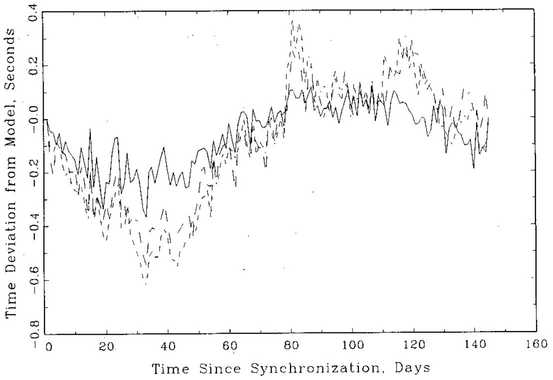

Fig. 4. The residuals of the clocks of Fig. 3, respectively, after removing an estimate of frequency drift, frequency offset, and a mean time from each of them.

mation using ASCII data transmission relevant to timekeeping, as well as providing on "on-time" character at the user's computer.

A major problem in any synchronization is calibrating the delay in the path used to communicate time. The ACTS achieves this by requiring the user's system to echo back the on-time character when it is received, then measuring the time for the round trip of that character to the user and back. The ACTS then advances the transmission of the next on-time character by one-half of the measured delay, so it arrives at the user's computer on time, within the limits of reciprocity.

IV. SUMMARY

The Smart Clock provides a framework for improving accuracy or stability of a clock by applying corrections based upon optimal use of measurements against an external reference. The system can compensate for systematic offsets of time, frequency, and drift of frequency, as well as various types of random effects. The algorithm uses optimal estimation to characterize the random effects and to predict the error of the oscillator or clock. The system can also account for various environmental effects using environmental measurements. There are a variety of communication and measurement systems which could be used to provide access to an external time standard.

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