TA0344
Technical article

Highly accurate, automatic temperature-compensated real-time clock (RTC) solution

Introduction

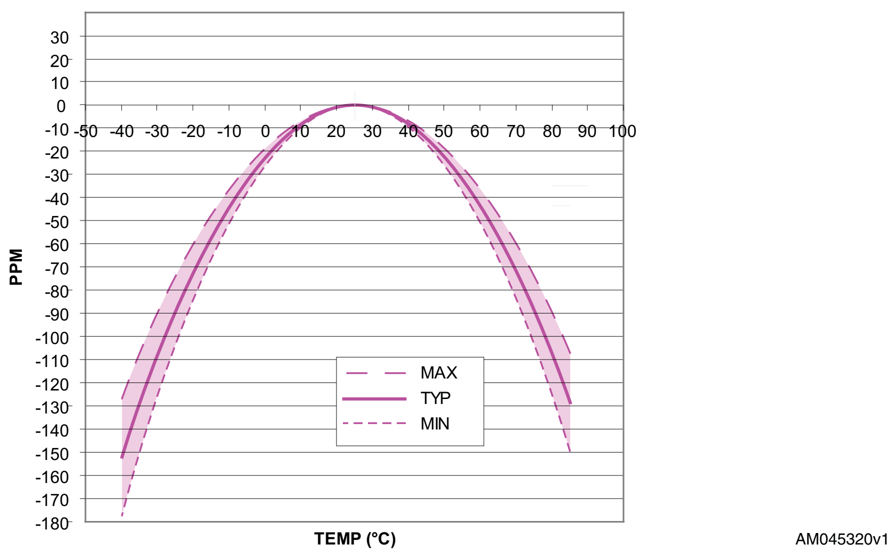
The requirements for higher accuracy are driving innovative solutions for improved timekeeping. More and more applications now require very accurate timekeeping across a wide range of temperature. Multi-rate smart power metering is a typical example in this field since power companies need to log multi-rate electricity usage for accurate billing. This normally requires less than ±0.5 seconds per day to a reference temperature of 23 °C, that is, ±6 ppm (parts per million) accuracy. Across the temperature range of -25 °C to +60 °C, the accuracy must be within ±1 second per day (that is, ±12 ppm), according to the latest Chinese power metering standard Q/GDW 357-2009. Given this criteria, a typical real-time clock (RTC) cannot fulfill the application requirements. Several possible solutions for better timekeeping accuracy are described in this article, while also proposing a preferred solution.

The challenge

Typical real-time clocks employ 32.768 kHz quartz tuning fork watch crystals. These are readily available and relatively inexpensive. Normally a crystal can provide accuracy of approximately ±25 ppm, or about 2 seconds per day at 25°C. While being well-suited to the low-power needs of battery-backed applications, their frequency can vary significantly over the industrial temperature range from -40 °C to +85 °C. At extreme temperatures, frequency errors are somewhere between -108 ppm and -177 ppm as shown in *Figure 1*. The resulting time loss can be as much as 10 to 16 seconds per day.

The frequency error due to the inherent crystal characteristic is parabolic, and the timekeeping of the RTC can only be as accurate as its reference (the crystal).

Figure 1. Typical 32.768 kHz frequency error versus temperature



Possible solutions for improved timekeeping accuracy

Crystal screening

There are many approaches to improving the timekeeping of RTCs. The first and easiest way is to improve the specification of the reference (the crystal). An accuracy of ±10 ppm or even ±5 ppm can be obtained by crystal screening. Although it is possible, crystal screening is not optimal since it is costly for the manufacturer to grade the crystals into a tight accuracy range. The most important limitation is that screening is only possible at one temperature point (for example room temperature). The parabolic nature of the frequency deviation across temperature is still present.

Crystal molded inside of the RTC package

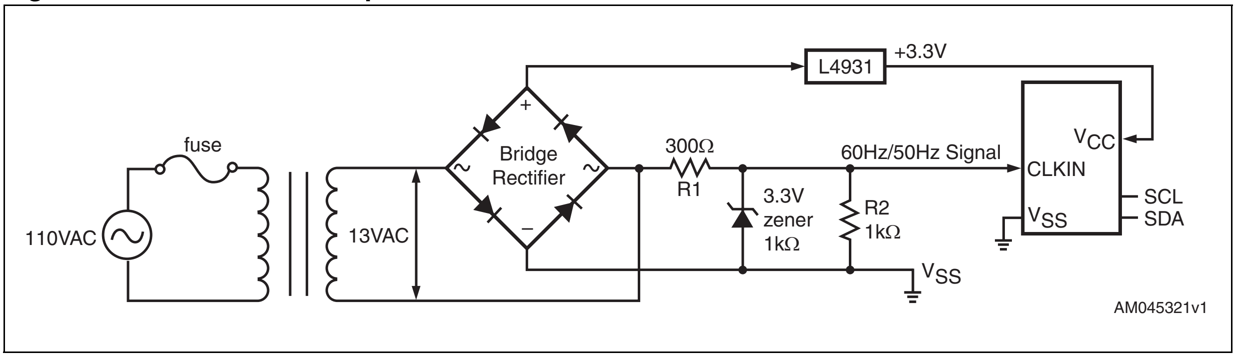
Molding the crystal into the RTC package is a good solution to improve the timekeeping accuracy since several environmental factors like humidity, vibration and pressure can influence RTC accuracy, but this alone does not resolve the inferior frequency characteristics of a quartz crystal over temperature which causes clock inaccuracy when the temperature is changing.

Using a 60 Hz power line as reference

The main idea of this solution is to convert the 60 Hz power (used in the U.S. as an example) to a useable clock source. The frequency error from the power line is much smaller than a conventional crystal. This AC power source must then be converted into an appropriate frequency source for an RTC device. The input of most RTC devices requires the common 32.768 kHz crystal oscillator, which is internally divided to provide a one second clock. Most RTCs cannot accept a 60 Hz clock, so a PLL is needed to correct the frequency input for the RTC. Moreover, the 60 Hz clock is not a submultiple of 32,768, so it needs to be divided down to a common factor before entering the PLL. This solution involves multiple steps which may not be suitable for some users.

Some RTCs can accept a frequency of 60 Hz as the clock source. Although this improved solution eliminates the need for a PLL, the circuit as shown in *Figure 2* remains too complex for some users. The accuracy of the RTC cannot be guaranteed when the main power is lost.

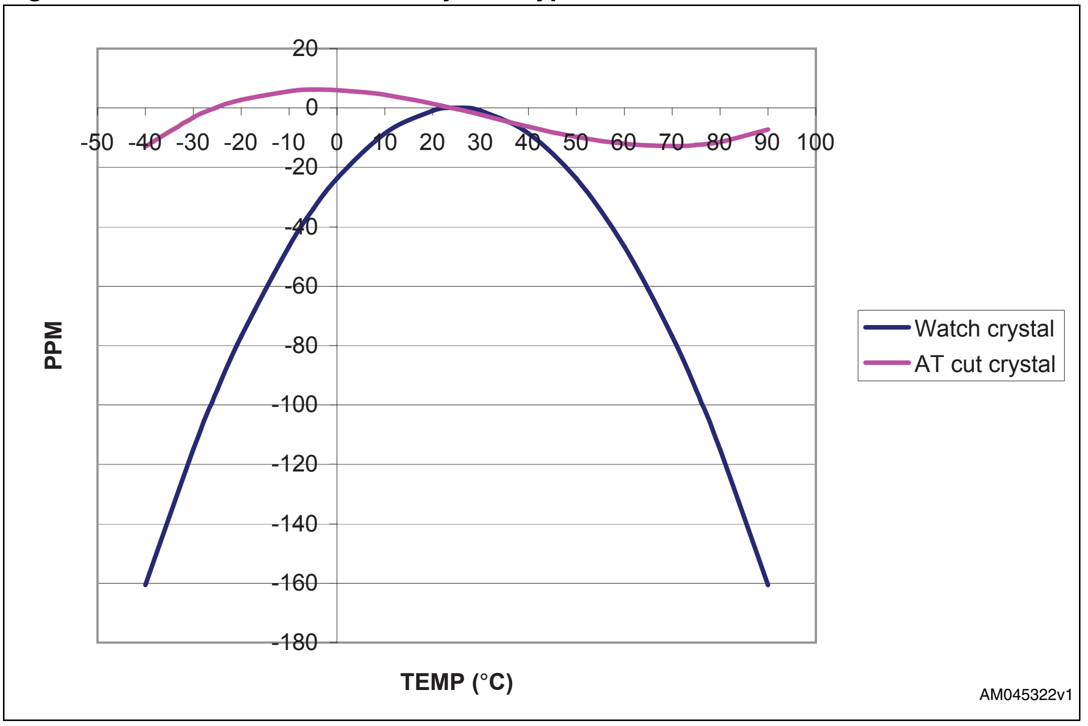
Figure 2. 60 Hz sine wave preservation



Using AT-cut crystals

Another possible solution is to use AT-cut crystals. The higher speed, AT-cut crystals used with microprocessors have lower error over a wide temperature range, and can thus provide higher accuracy, but their oscillators are not suitable for low-power applications since they draw much more current at the frequencies common for AT-cut crystals. The AT-cut crystal error is shown in *Figure 3*.

Figure 3. AT-cut versus watch crystal - typical characteristics



The key concept of this solution is that the MCU's timer runs off a clock signal derived from the MCU's AT-cut crystal oscillator. Since this crystal has low error over temperature, the timer's clock signal will also have low error. Therefore, using this timer, the RTC can be calibrated to approach the accuracy of this clock source, thus reducing the timekeeping errors associated with watch crystals due to temperature drift.

Application note AN2678 (“Extremely accurate timekeeping over temperature using adaptive calibration”) from ST gives a detailed description of using the AT-cut crystal to compensate the M41T82-83-93 series RTCs so that higher accuracy over a wide temperature range can be obtained.

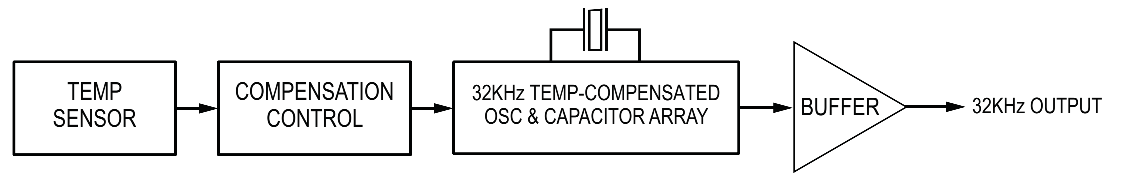
The relatively accurate clock sources mentioned above are only some of the possible options. Other clock sources such as a remote system clock from the internet or from a satellite are possible too.

Using TCXO

Another possible solution is to use a TCXO (temperature-compensated crystal oscillator) to replace the basic quartz crystal which improves timekeeping at the source. The TCXO has the temperature sensor inside of the device and can flatten the parabolic crystal curve over a wide temperature range which produces an accuracy of ±5 ppm, but this solution represents a more costly approach.

A typical TCXO block diagram is given in *Figure 4*. The crystal and the compensation circuit are integrated, but this increases the price of a TCXO which is at least 3 times that of a normal crystal.

Figure 4. TCXO block diagram



Using temperature compensation

At the system level, if an external temperature sensor is present and is located near the RTC and its crystal, it can be used to considerably improve accuracy. Only extra application software is required, thereby avoiding the need for additional components.

Application note AN2971 ("Using the typical temperature characteristics of 32 KHz crystal to compensate the M41T83 and the M41T93 serial real-time clocks") from ST describes a detailed solution using a temperature sensor on a system level to improve the accuracy of the M41T83-93 series RTCs.

The idea is to first prepare a ΔPPM (variation from the reference frequency of 32,768 Hz) vs. temperature table (look-up table) since the crystal parabolic curve is normally known and then follow these steps:

1. Measure the temperature and then find the ΔPPM in the look-up table.
2. Adjust the analog calibration register to change the load capacitance on CXI and CXO (internal capacitance array connected to XI and XO pins).

The analog calibration is integrated in the RTC so that the load capacitance change seen by the crystal will slow down/speed up the oscillation frequency.

These devices can also be digitally calibrated. The concept of digital calibration is simply to add or subtract pulses periodically into the clock chain to speed up/slow down the clock.

Regardless of whether analog or digital calibration is used, temperature compensation at the system level requires a temperature sensor on the board and an RTC with internal calibration capability in addition to significant software development.

Best solution - an embedded crystal temperature-compensated RTC

All of the solutions mentioned above are either costly or add complexity to the system. They either cannot significantly solve the temperature error issue or they rely on an external temperature sensor, power line or MCU with significant associated software development costs. The biggest drawback is that even when temperature compensation is used, it doesn't work in battery backup mode when the main supply is off. A better solution is needed!

The optimal solution should have the following characteristics:

1. Integrate the crystal, temperature sensor and RTC together in a single package
2. Efficient compensation algorithm for timekeeping accuracy over -40 °C to 85 °C
3. Low power consumption especially during battery backup mode
4. User friendly. No software development required at system level
5. Low cost

The M41TC8025 from ST represents a complete solution, combining cost effectiveness with no additional development effort. The crystal, temperature sensor and RTC together with the automatic compensation algorithm are all integrated into a single package. Very accurate (±5 ppm) timekeeping is obtained over a wide range of temperature from -40 °C to 85 °C with a very simple external hook-up circuit as shown in *Figure 6*. The timekeeping accuracy improves to ±3.8 ppm within the range of 0 °C to 50 °C which exceeds the requirements of most applications including smart power meters.

Block diagram and hardware hookup of the M41TC8025

Figure 5 shows the M41TC8025 temperature-compensated RTC block diagram. The common quartz crystal with the temperature sensor and the compensation algorithm provides a very accurate 32.768 Hz clock source. The segmented clock chain gives ultra-accurate clock and calendar values which can be easily accessed via the I^2C bus.

Figure 5. M41TC8025 temperature-compensated RTC block diagram

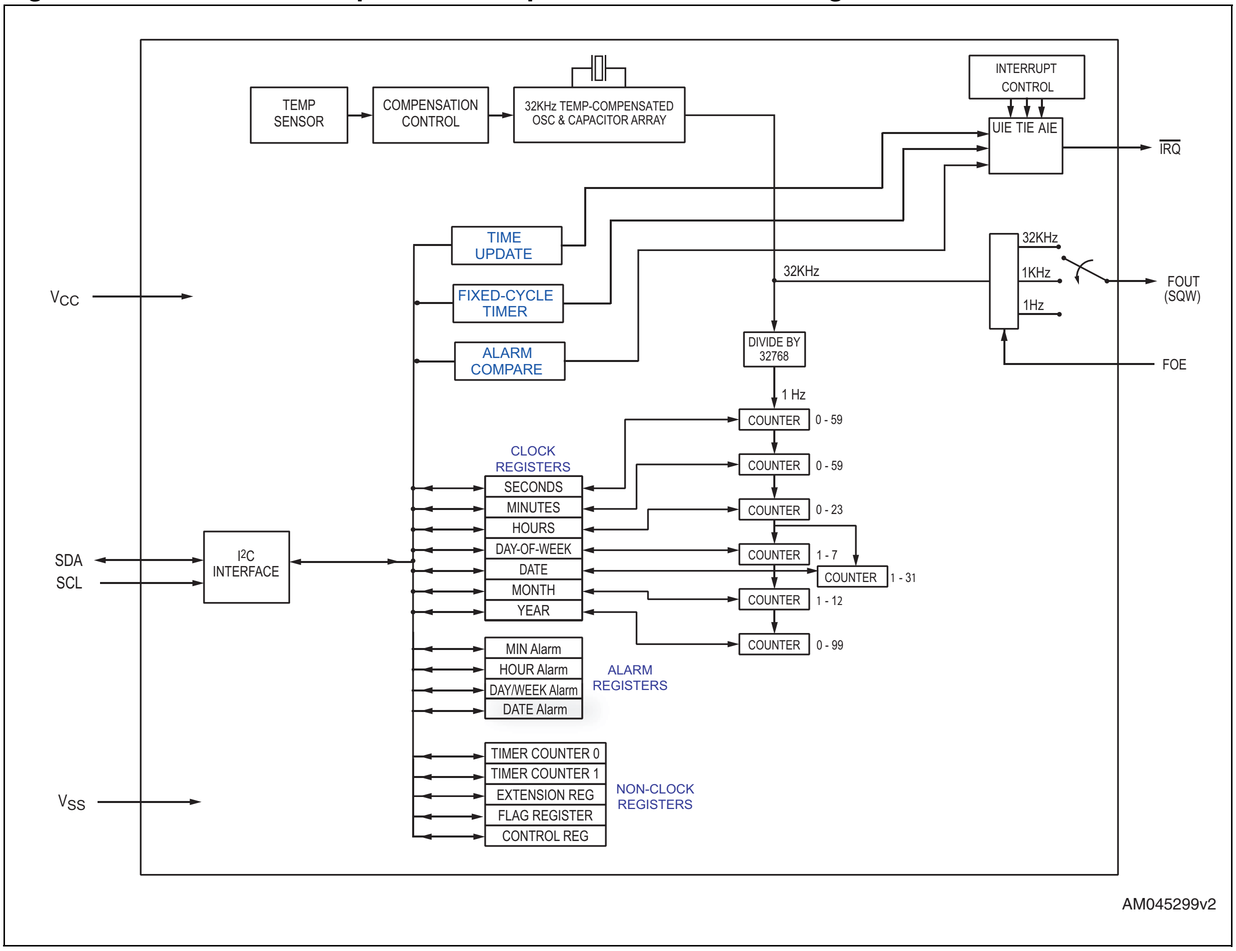
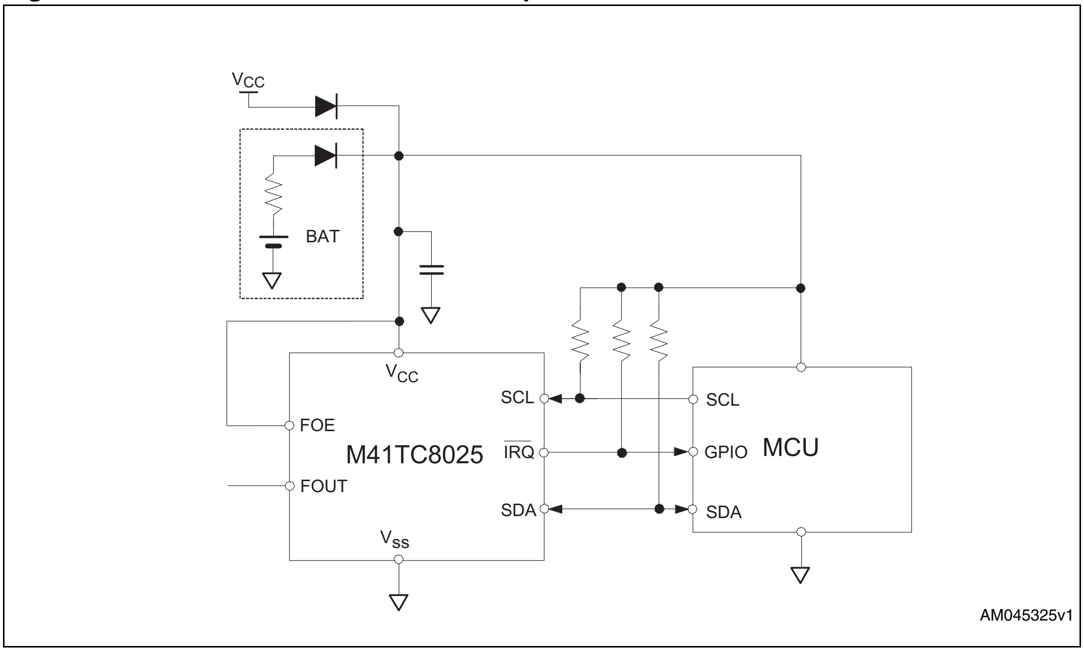


Figure 6 below shows the M41TC8025 hardware hook-up diagram. The battery backup switchover function can be obtained using two diodes to avoid reverse-charging of the primary cell battery.

Figure 6. M41TC8025 hardware hook-up



Additional features of the M41TC8025

In addition to very accurate timekeeping, the M41TC8025 has other useful features:

- The alarm allows setting a future event condition which will give the signal on the $\overline{IRQ}$ (interrupt) pin.
- The time update (seconds update or minutes update, user-configurable) is also available on the $\overline{IRQ}$ pin.
- The fixed-cycle timer interrupt function generates a periodic square wave on $\overline{IRQ}$ at any fixed-cycle programmable between 244.14 µs and 4095 minutes.
- The FOUT pin of the RTC provides a programmable, accurate 1 Hz, 1,024 Hz and 32,768 Hz frequency outputs for an easy accuracy test during product manufacturing. FOUT can be disabled by grounding the external enable pin (FOE).
- Although the M41TC8025 has an ultra-low power consumption of 0.8 µA typical current at 3.0 V supply voltage, it also allows the user to configure the temperature compensation period to customize accuracy versus power consumption.
- The device provides a flag to indicate low supply voltage when that condition occurs.

For more detailed information about M41TC8025, please refer to the datasheet on *www.st.com*.

Conclusion

The requirements for higher accuracy are driving innovative solutions for improved timekeeping. In the M41TC8025, STMicroelectronics offers a fully-integrated device which includes the crystal, temperature sensor, automatic algorithm for temperature compensation and the RTC in a convenient, single package. This solution provides extremely accurate timekeeping at a low cost and represents the best choice for applications which require high accuracy such as smart power metering.

Revision history

Table 1. Document revision history

Date	Revision	Changes
27-Sep-2012	1	Initial release.