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FROM THE BENCH

by Jeff Bachiochi

Light-to-Frequency Conversion (Part 1)

TSL230R-Based Pulse Oximeter

TAOS light-to-frequency converters are becoming increasingly popular amongst designers whose applications require light-sensing capabilities. One reason why is because designers want digital output rather than analog. In this column, Jeff explains why a TAOS TSL230R is the perfect part for the pulse oximeters used in hospitals.

I grew up reading Spiderman, Superman, the Fantastic Four, and other comics. I always seemed to be able to scrape up the 12 cents or so needed to stay current with new issues. Comics were to me as baseball cards were to most youths at the time. Instead of dreaming of putting on pinstripes or red socks, I wanted colored spandex and the superpowers that were associated with them. Please don't ask me to reveal my secret identity here. Obviously, that would give those on the dark side an edge.

The back pages of most comic books contain items for sale that feed upon a child's fantasies: magic tricks, joke items, switchblade combs, and unusual pets—you name it. X-ray glasses have been a popular item for years. A small hand-drawn picture is often the selling point for the product. A curvaceous female is all that's necessary to get the mind reeling. As you can guess, cheap frames with cardboard lenses won't exactly allow you to see someone's bones and anatomical points of interest. However, the medical industry has an arsenal of such machinery at their beckon call.

Seeing into the body brings with it the advantage of noninvasive diagnosis. Luckily for patients, bloodletting pretty much has been replaced as a cure-all. In fact, many of today's medical procedures don't require a patient to be opened up at all. Various endoscopic surgical techniques require only a minor incision (or sometimes none at all) to inspect, diagnose, and even repair internal problems. The medical professional has progressed from butcher to miracle worker. Nevertheless, there's plenty of room for improvement.

I remember Dr. Kristan coming to my house and using his stethoscope on me when I was sick as a child. He'd place the cold disk on my body and ask me to breath heavily. Connected to the disk were black tubes that ran to his ears. I always asked if I could listen, and he was never too busy to let me. Stethoscopes have not changed much since then; most don't require a power source for operation. Other equipment, however, is more complicated. From diagnostics to database management, computers and electronics now play an integral role in the medical field.

If you've been a hospital patient, an electronic device undoubtedly has monitored your heartbeat. Devices like stethoscopes monitor heartbeats acoustically; other devices measure pressure. Then there are the devices that monitor the light modulation resulting from the pulsing flow of blood. This has become the prevalent technology thanks to the photodiode, which produces a current proportional to the amount of light hitting its PN junction. In this two-part series, I'll show you how new technology enables healthcare professionals to monitor the light absorbed through living tissue.

LIGHT ABSORPTION

My sisters and I rarely got to play with flashlights as kids. But as dusk fell on Halloween, we were given a flashlight to guide our way between tricks and treats. The light beam often found its way into our mouths as we tried turning our heads into jack-o'-lanterns. Glowing, red cheeks seemed appropriate on All Hollow's Eve. When light passes through your body, your bones, tissues, and fluids absorb a lot of it. Comparing the intensity of the light that makes its way out (X_{OUT}) to that which comes in (X_{IN}) gives you the percentage of light that has passed through your body. Subtracting this percentage from 100% gives you the percentage of light absorbed by the body.

Arteries and veins carry blood throughout the body. They expand and contract with each heartbeat. During the systolic phase, the heart contracts, pushing blood into arteries, capillaries, and veins. Blood flows back to the heart from

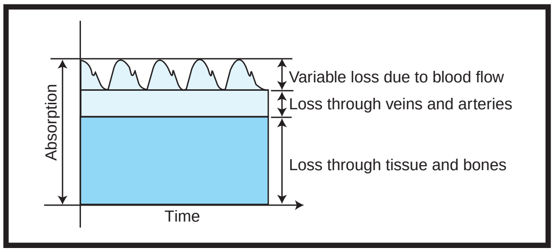

Figure 1—*Check out how various tissues and bones can absorb light transmitted through the body. As blood flows through the circulatory system, it changes density because of the heart's pumping pressure. This change also changes the absorption rate of light, effectively modulating the light absorption. The total light absorption is a combination of modulated and constant absorption, which is similar to a small AC noise riding atop a DC voltage.*

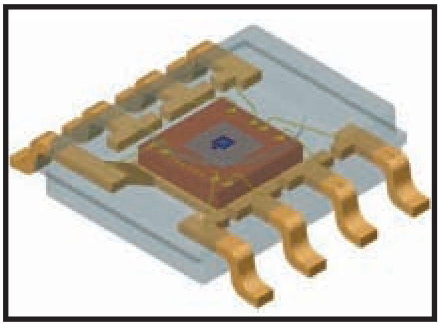

Figure 2—*This eight-pin sensor is molded in clear plastic. It has a visible array of photodiodes. Mode inputs to the device enable an array of one, 10, or 100 photodiodes to select the sensitivity.*

the veins during the diastolic (resting) phase. As the arterial system expands and contracts, it affects the level of light absorption. This adds an AC component to the background absorption (or DC level), as you can see in Figure 1. The DC and AC levels might change drastically depending on where on the body the measurements are taken. Earlobes and fingers used most often because they are relatively thin and easily accessed.

Using a photodiode to measure intensity requires fairly high amplification. Care must be taken to minimize the noise in the external circuitry necessary to create an analog signal large enough to be read with an A/D converter. A light-to-frequency converter can replace most of the sensitive circuitry as the light-monitoring device for the sensor application.

TAOS

In 1999, Texas Advanced Optoelectronic Solutions (TAOS) acquired licensing to produce and market the optoelectronic family of sensors from Texas Instruments. Its mission has been to develop and manufacture semiconductor devices combining photodetectors with precision mixed-signal functionality to give you a light-sensing solution with improved performance and design simplicity. TAOS products include light-to-voltage, light-to-frequency, linear-array, ambient, color, and color-reflective optosensors.

For this project, I chose the TSL230R for its sensitivity and wide spectral response. This programmable light-to-frequency converter has an array of photodiodes and a current-to-frequency converter in an eight-pin package. All the I/O is TTL-compatible, so analog isn't involved. This removes any concerns associated with small analog signals.

Although a photodiode array isn't mentioned in the TSL230R datasheet, you can see a 10 × 10 array on the device (see Figure 2). Two inputs to the TSL230R are used to select the device's sensitivity. Selections include 1×, 10×, and 100×, which leads me to surmise that these selections choose the array size of the photodiodes. Using the 100× selection, device responsiveness is given as 770 Hz/µW/cm^2. The spectral bandwidth covers the two areas of interest pertaining to this project: red (600–700 nm) and infrared (800–940 nm). Although the frequency out is directly proportional to the light intensity, total darkness is not represented by zero frequency. The device always produces output. The minimum might be approximately 1 Hz. At 100 µW, the maximum

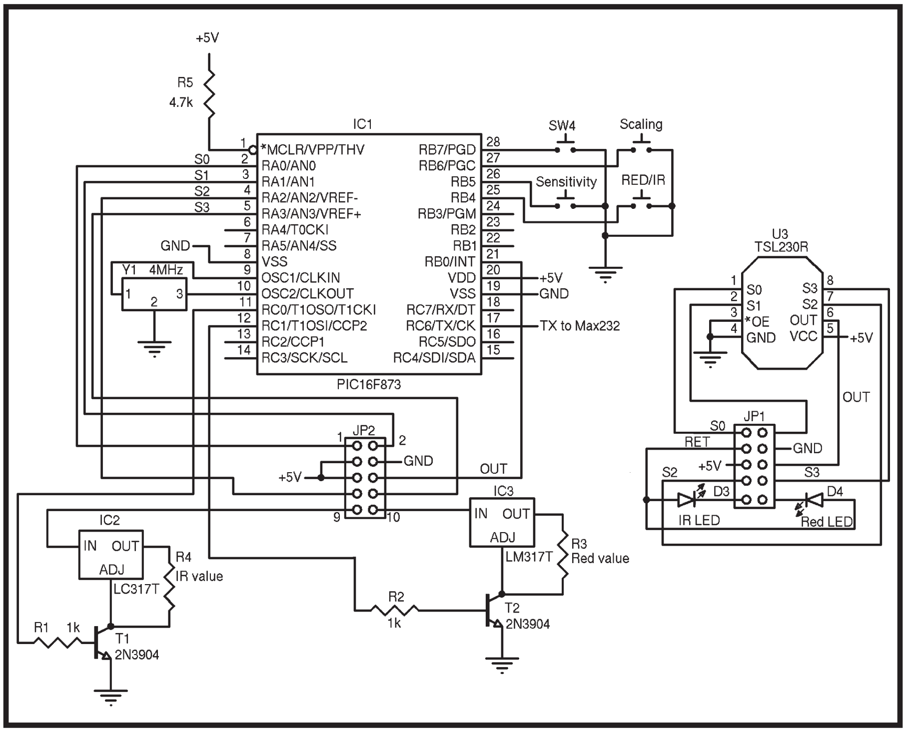

Figure 3—*The lower circuit shows the sensor module in Photo 1. A ribbon cable connects the sensor unit to the upper circuit located on the bench for easy experimenting. I didn't include the level-shifting circuitry that makes the TX sample data available to a PC.*

frequency is approximately 100 kHz (using the 100× mode—the complete array). As expected, the 10× and 1× modes produce this frequency at 10× and 100× the light level of the 100× mode.

The eight-pin TSL230R consists of the photodiode array (with its two sensitivity inputs) with a current-to-frequency converter. Two other inputs select a divisor for the output frequency. This leaves connections for power, ground, frequency output, and an output enable input.

DESIGN PARAMETERS

A heart rate in the vicinity of 70 beats per minute (bpm) is considered normal for an adult. A newborn's heart rate is typically around 120 bpm. Your heart rate slows to approximately 50 bpm as you enter your golden years. When exercising, your heart rate may double. (Sustained exercising need only elevate the normal heart rate by roughly an additional 50% to be effective.) Accounting for all of this data, I'd limit what could be considered good readings to, say, 50 to 200 bpm.

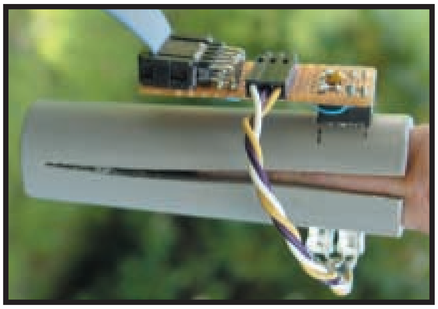

Photo 1—*A slot is cut most of the way through a small section of plastic electrical conduit, which houses both the TSL230R sensor and the red and IR LEDs. The TSL230R registers the amount of light passing through the inside diameter of the conduit, which, in this case, is through a victim's, eh, patient's, finger.*

Figure 3 shows the circuit I used for experimenting with this project. It may be overkill for the end product, but I can have the hardware serial port on the microcontroller output some data for analysis. I'll consider using a smaller device when I don't need to log any data. Although it's possible to drive an LED directly from the microcontroller's I/O, any change in voltage will have a different effect on the current through each LED because the LEDs have different drops. I chose to use constant current drivers for the two LEDs. This automatically takes into account the different drops for the red and IR LEDs.

The TSL230R and LEDs are a sensor unit connected to the electronics with a 10-conductor ribbon cable (see Photo 1). Figure 3 shows how it's split. This allows the sensor to connect to various prototype circuits.

I found a piece of plastic conduit that fit over my finger after I slotted it. By slotting all but a 0.25″, it acts like a clothespin and holds on firmly to my finger without being uncomfortable. The TSL230R sensor is glued into a square hole placed on one side of the conduit. The red and IR LEDs are forced into two drill holes directly across the diameter from the sensor. Square pin headers make all the connections easier.

SMT and flex circuitry would be perfect for this application. I did not experiment with mounting the LEDs and sensor on the same side of the conduit. Although this becomes more of a reflective illumination, it avoids having wires span two moving objects, which is a potential mechanical point of failure.

Because I used a red LED and an IR LED, the circuit can actually measure the oxygen content of your blood in addition to your heart rate. To measure a heart rate, you must calculate the time between the maximum (or minimum) excursions of the AC portion of the light absorption output. Both the red LED and the IR LED can provide the light source for the TSL230R. However, the hemoglobin in red blood cells picks up oxygen molecules in the lungs and becomes a brighter shade of red, which will absorb less red light.

Figure 4 shows the difference in light absorption between oxygenated and deoxygenated blood at various wavelengths. Notice that for infrared there is little difference in the absorption. At lower wavelengths (especially the red region), there is a significant

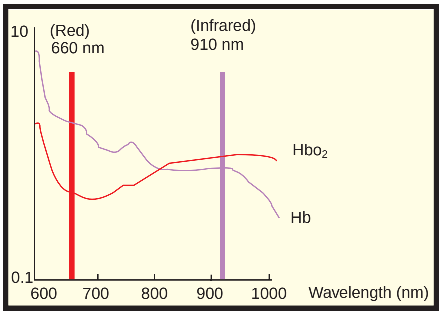

Figure 4—*Study the absorption relationship of oxygen levels in the blood for the red and IR wavelengths. Notice how the oxygen level affects the absorption rate at the red wavelength while it remains almost constant at IR wavelengths.*

difference. You can calculate the level of oxygen by comparing the absorption outputs of each light source separately.

AC VERSUS DC

In order to be successful, you must be able to measure the AC component of the sensor's output. What can you expect as a signal? Photo 2 shows the TSL230R's output. The vertical scope cursors show the minimum and maximum excursion of the frequency output (with the sensor on a finger). In /100 mode, a full cycle (DC portion) measures approximately 3.5 ms, and the AC portion is approximately 215 µs. In /1 mode, a 35-µs cycle has only 2 µs of AC.

There are two methods for taking samples. The device's frequency output is directly related to light intensity falling on the sensor, so one cycle is sufficient as a sample. In the first case, you need only measure the period of one cycle to obtain a sample. Keep in mind that the output in /1 mode is a period and not a symmetrical square wave as in /2, /10, and /100 modes. This means that one must measure a full cycle in /1 mode as opposed to a minimum half cycle in the other divided modes. (Or at least be sure you are measuring the right half.) Although the percentage of AC to DC is the same with all output modes, a 1-µs clock is useless in this case with a /1 output (in the aforementioned example). The most desirable output is one that approaches the sampling rate but doesn't create timing interference with other functions.

Another way to look at data would be to average the output over the duration of the sampling period. The TSL230R does this for you to some extent. For instance, /100 mode gives an output equal to the sum of 100 cycles. However, using this method, you want this sum to be for the duration of the sample period and not a certain number of cycles. In this case, you want just the opposite of the first method. You want the fastest output you can count, so that the DC (and the AC) portion will have the largest count possible. Because the AC is roughly 6%, you can expect an AC count of ±3 for every 100 counts of DC. Using the same numbers as the first method, the 35-µs output would have approximately 880 counts in one sample period. Using the /100 output of 3.3 ms would have only eight counts!

DIGITAL CONNECTION

Unlike Analog sensors, the TSL230R doesn't require an A/D converter to get values into a microcontroller. The TTL-compatible output makes a direct interface possible to a microcontroller without the need for analog signal conditioning. If the sensor is at any distance from the rest of the electronics, a shielded cable isn't necessary because low-level noise sensitive signals aren't used. Applying the sensor's frequency output to a microcontroller's external interrupt input can simplify period or pulse counting. Although I hope the final circuit won't need any active mode control for the TSL230R, having total control of the mode input pins makes experimenting much easier. A PIC running at 4 MHz has a 1-µs execution cycle, which is a nice whole number to work with for timing. A 16-bit timer using this 1 µs as the timebase can count up to ~65 ms before rolling over.

The timer's count is directly related to the irradiance level. The smaller the count, the higher the frequency and the more light falling on the sensor. To make sense of this, you need to grab samples at a fixed rate (at least two times faster than the frequency of interest – Nyquist). For 200 bpm, or 3.3 bps, that would be approximately 7 Hz. I used a sample rate of 32 Hz (31.25 ms) for this project because it fits nicely into this timer's range.

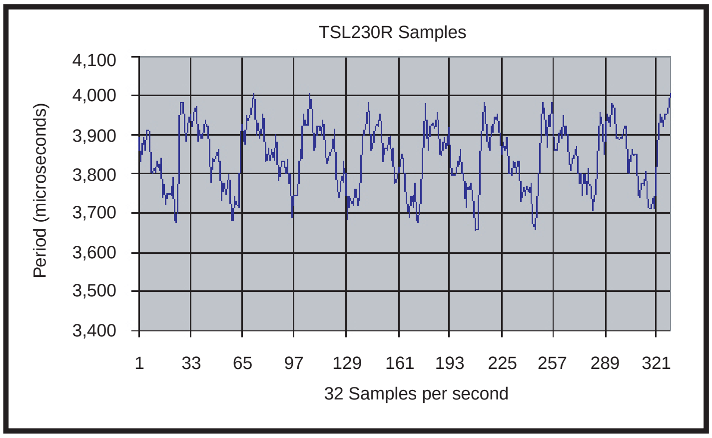

Figure 5—*This Excel chart displays imported sample values over time. Samples of the output frequency (30 samples per second formatted in microseconds) were sent out the serial port and captured to a file by HyperTerminal.*

Timer1's overflow is set to 31.25 ms by loading the timer's count with a constant at each overflow. Because of interrupt latency and instruction cycles for the interrupt routine code up to the point where the timer is loaded and begins counting, the actual value placed in the counter will be less than what's required for 31,250 counts. The timer counts up to overflow, so the required value of counts must be subtracted from the rollover count (or the value complemented). A simulator (with a stopwatch or instruction counter) is helpful for determining the exact value necessary to obtain accurate timing.

The frequency of the TSL230R will increase as more light falls on its light-sensitive array. Although the sensor doesn't produce zero frequency output for zero irradiance, the output is linear. Using the most sensitive mode, the maximum frequency could be 100 kHz (130 µW/cm^2 at 640 nm) with a minimum frequency of approximately 1 Hz. This maximum frequency equals a Timer1 count of 10 with a Timer1 overflow at a minimum frequency because the 16-bit timer overflows at approximately 31 ms.

The only way to achieve a minimum frequency is with little or no irradiance. A Timer1 overflow can indicate an error or too little light. Too much light is a bit trickier to detect. A count of 10 would be impossible to detect in this case because the code execution for the interrupt lasts longer than the 10 µs for a period. So, counting edges (periods) would be missed and the count wouldn't be accurate.

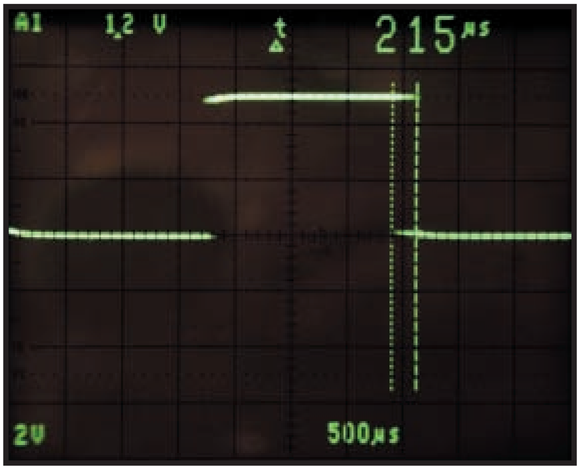

Photo 2—*The TSL230R's frequency output displayed on my oscilloscope shows a slow frequency jitter marked by the vertical cursors. The output frequency shifts with the varying amount of light absorption because of the blood pulsing within the light's path.*

The instantaneous sampling approach requires the frequency to be measured once each sample period. This is achieved by enabling the external interrupt each time Timer1 overflows (31.25-ms sampling timer). After the external interrupt is enabled, Timer1's count is sampled twice on each of the next two rising edges of the TSL230R frequency output. The difference in the two counts equals the period of the output in microseconds for that sampling period.

The sampling sum approach uses Timer1's overflow (31.25-ms sampling timer) to read the accumulated period count and then flush it every sample period. The external interrupt is always enabled. Each rising edge of the TSL230R's frequency output adds one to the number of periods. The accumulated count at each sample time is the sum of all the periods output during that sample time. This is essentially a period average for that 31.25 ms.

SAMPLING

Next month, I'll describe the process of choosing the appropriate mode and making sense out of the samples. In the meantime, study Figure 5, which shows some TSL230R samples. I used the on-board UART to dump each sample in a five-digit decimal number (followed by a CR). I imported these into Excel and used the graphing function to show you what's going on. I'll use this to determine how to manipulate the data into an indication of beats per minute. ■

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RESOURCES

Omimeter.org, "Principles of Pulse Oximetry Technology," 2002, www.oximeter.org/pulseox/principles.htm.

TAOS, Inc., "Pulse Oximetry," www.taosinc.com/downloads/pdf/pulse.pdf.

———"TSL230R, TSL230AR, TSL230BR: Programmable Light-to-Frequency Converters," TAOS048A, 2004.

SOURCE

TSL230R Light-to-frequency converter
TAOS, Inc.
www.taosinc.com