When Every µA Counts!

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Measuring multiple parameters, accurate readings, and having a long battery lifetime—these are the most critical parameters for a wearable health device.

Since the first pedometer came on the market 10 years ago, a lot has been changed. Initially, the measurement was focused on just step counting. Studies have been done for decennia with the outcome that 10,000 steps a day would give a good balance on calorie intake vs. the amount of calories burned. In the meantime, additional functions and features have been added to the wearable device such as measuring heart rate, heart rate variability, body temperature, and skin conductance. The wearable device, which initially was meant for sports and wellness purposes, is now moving slowly toward a more medical market. With this transition, we have to rely more on the accuracy of the measurements and battery lifetime. The longer the device runs from a single battery charge, the easier it will be to get it adopted by the user.

In this article, a new generation of products for wearable health devices is described, including tips and tricks on how they can make your system more reliable and power efficient.

PPG for Heart Rate Measurement

When it comes to our health, one of the most important organs in our body is the heart. It can be seen as the engine of our human system. Without a well-performing heart, we can face serious health issues. Monitoring the heart function for that reason is a key priority. There are many good reasons for checking our heart rate that go beyond the number of beats per minute. Besides that, we can retrieve a significant amount of additional information from the behavior of the heart in terms of the frequency as function of activity. When more activity is asked from the body, the heart rate should go up to bring more nutritious and oxygenated blood to the cells. A continuous high heart rate is not good, and neither is a fast changing heart rate, which could be an indicator of a cardiac disease such as atrial fibrillation.

Besides monitoring heart frequency, there is another parameter called heart rate variability (HRV). When people are relaxed, their heart won't beat with a fixed number of beats per minute, but you should experience a slight variation around the heart frequency, something in the range of ±3 beats per minute. This variation is an indicator for being relaxed. At the moment people get stressed or get a startled response, the adrenalin level in the body goes up and the heart starts pumping with a very monotonic frequency. For that reason the parameter HRV is important to monitor.

The classical way for retrieving cardiac signals is by biopotential measurement with an electrocardiogram (ECG); however, this is not easy to integrate in a wearable device.

A trend for measuring heart rate, other than biopotential, is by making use of an optical principle. This technology has existed for quite some time and is called photoplethysmogram (PPG). PPG technology mainly has been used in systems for measuring oxygen saturation in the blood (SPO2). For SPO2 measurement you are sending two wavelengths of light through a particular part of the body (usually the finger or earlobe) and you measure the percentage of oxygenated hemoglobin vs. the total amount of hemoglobin. Since this technology also allows you to measure heart rate, it is commonly used in wearable systems such as small wrist-worn devices, and unlike with biopotential measurement, it is possible to pick up the heart rate using a single measurement point. The ADPD174 from Analog Devices is an optical subsystem that has been designed to support these applications (see Figure 1).

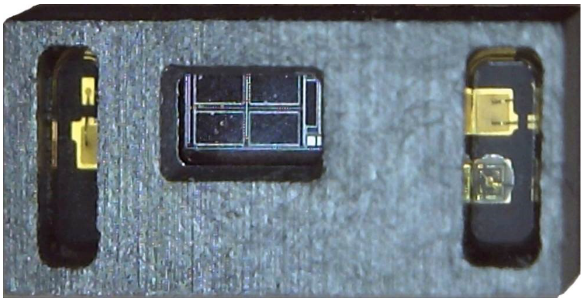

Figure 1. ADPD174, optical 6.5 mm × 2.8 mm system in a single package.

Reflective vs. Transmission

As most of us are familiar with SPO2 measurement, this is usually performed with a clip on the finger of earlobe. Light is sent through a part of the body and at the opposite site the received signals are being measured by a photodiode. With this transmission technique, we are measuring the amount of received or nonabsorbed light. This principle is best-in-class, in terms of signal performance vs. the amount of power spent. Integration of transmissive measurement, however, isn't an easy task in a wearable system where comfort is key—therefore, reflective measurement is more commonly used. In a reflective optical system, light is sent into the surface of the tissue, where a part is absorbed by the red blood cells and the remaining light is reflected back up to the tissue surface and measured by a photo sensor. In a reflective system, the receive signals are up to 60 dB weaker, so we need to pay more attention to our transmit and receive signal chain on both electrical and the optical aspects.

Electronic and Mechanical Challenges

During the time of a heart beat, the flow and volume of blood is changing, resulting in the scattering of the amount of reflected light received. The wavelength of the light that is used for measuring the PPG signals can vary depending on a number of factors—the first being the type of measurement. In this article, we limit ourselves to the measurement of just heart rate and its variation. For this measurement, the required wavelength depends not only on the location on the body that we are measuring, but also on the relative perfusion level, temperature of the tissue, and color tone of the tissue. In general for wrist-worn devices, where arteries are not located on top of the wrist, you need to pick up pulsatile components from veins and capillaries just under the skin surface. Green light in these applications give us the best receive. At places where you have enough blood flow, like the upper arm, temple, or ear canal, red or infrared will be more effective, as it penetrates deeper into the tissue—especially for wearable application where battery power and size is always an issue, red or IR LEDs bring an additional advantage, as these require a lower forward voltage. For applications where coin cell batteries are used, these LEDs can be driven directly from the battery voltage.

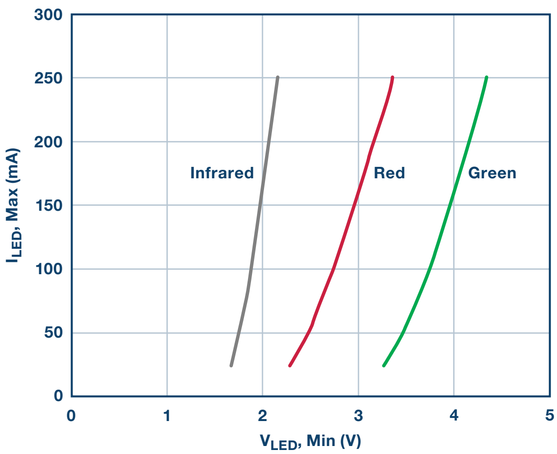

Figure 2. Required LED forward voltage vs. LED current.

Green LEDs, unfortunately, need a higher forward voltage that requires an additional boost converter, so it will have a negative impact on the overall current consumption of your system. Figure 2 shows the required forward voltage for different LED colors as function of the current. If green LEDs are still required, the ADP2503 buck/boost converter could be of help to support a higher LED forward voltage up to max 5.5 V, operated from an input voltage that can go as low as 2.3 V.

When trade offs such as sensor position and LED color are being made, the next step is to select the most appropriate optical solution. There are many choices in terms of analog front ends, either discretely built or fully integrated, but also there is a wide offering of photo sensors and LEDs that can be selected. To minimize design efforts and to shorten time to market, ADI built a fully integrated optical subsystem for reflective optical measurement. It is called the ADPD174, and contains everything needed to run an optical measurement. In Figure 3, you'll find the block diagram of the ADPD174 subsystem. The size of the module is 6.5 mm × 2.8 mm, which makes it extremely attractive for wearable systems.

The module is built around a big photodiode, two green LEDs, and an IR LED. The on-board mixed-signal ASIC includes an analog signal processing block, a SAR-type ADC, a digital signal processing block, an I²C communication interface, and three free programmable LED current sources.

The system drives the LEDs and measures the corresponding optical return signal with its 1.2 mm² photodiode. The biggest challenge for measuring PPG with a wearable device is to overcome interferers like ambient light and artifacts generated by motion. Ambient light can influence the measurement results incredibly. Sunlight is not too difficult to reject but in particular light from fluorescent and energy saving lamps, which include ac components, are difficult to cancel. The ADPD174 optical module has a two-stage ambient light rejection function. After the photo sensor and input amplifier stage, a band-pass filter is integrated, followed by a synchronous demodulator, to offer best-in-class rejection for ambient light and interferers from dc up to 100 kHz. The ADC has a resolution of 14 bits and up to 255 pulse values, which can be summed to get a 20-bit measurement. Additional resolution up to 27 bits can be achieved by accumulating multiple samples.

The ADPD174 operates in two independent timeslots—for instance, to measure two separate wavelengths and can carry out the results sequentially. During each timeslot, the complete signal path is executed, starting with LED stimulation followed by photo signal capturing and data processing.

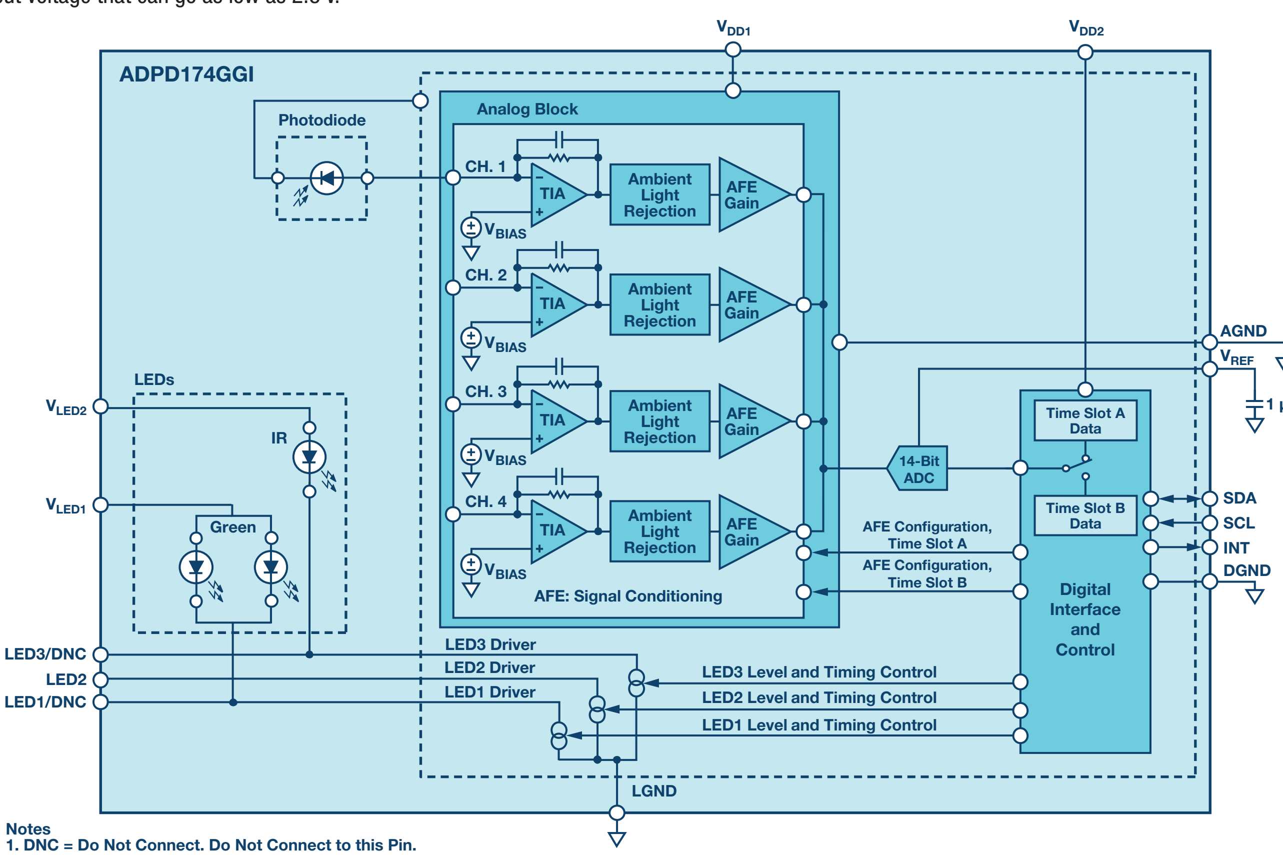

Figure 3. Block diagram of the ADPD174 optical subsystem.

Each current source is able to drive the connected LED with currents up to 250 mA. Innovative control over the pulsing of the LED keeps the average power dissipation low and contributes significantly to the savings of power and the battery life of the system.

The advantage of this LED driving circuit is that it is dynamic and scalable on the fly. There are many factors that can affect the signal-to-noise ratio (SNR) of the received optical signal, such as skin tone or hairs between sensor and skin, which impacts the sensitivity on the receiving side. For this reason the excitation of the LEDs can be configured very easily to build an autoadaptive system. All timing and synchronization is handled by the analog front end, so there is no overhead required from the microprocessor in the system. With the ADPD174 you will be able to run a reliable heart rate monitor in normal circumstances at a power level of around a milliwatt. To find this operating point, we can tune the gain of the transimpedance amplifier (TIA) in combination with setting the maximum LED peak current. After optimizing the LED current and TIA gain, we can increase the number of LED pulses to get more signal. Be aware that increasing the LED peak current is increasing the SNR proportionally, whereas increasing the number of pulses by a factor of n, results in an SNR improvement of the root of n ($\sqrt{n}$) only.

Finding the optimum settings for your heart rate device also depends heavily on the user. The user's skin tone has impact on the signal strength as well as device positioning, temperature, and blood flow. For calculating the power consumption, the optical front end can be seen as two separate power contributors, IADPD and ILED. IADPD is the current consumed by the input amplifier stage, the ADC, and the digital state machine. These power numbers very much depend on the sampling rate of the ADC. The LED current ILED will change with the person's skin tone and the position of the sensor on the body. For a darker skin tone more LED current is needed, as well as for the sensor position on the body when there is very little blood flow. The average LED current is changing with the LED drive pulse width, the number of pulses, and the ADC sampling time. The average LED current is the max LED current, multiplied by the pulse width and the number of pulses. This can be seen as one timeslot and repeats every time a new sample is taken. The pulse width can be as narrow as 1 µs.

For a good heart rate measurement on the wrist, an LED peak current is required of around 125 mA, when using two pulses with 1 µs width. Considering a 100 Hz sample frequency, the average LED drive takes 25 µA. When we add 250 µA average AFE current, the optical front end is consuming 275 µA (@ 3 V = 825 µW).

Additional Mechanical Challenges

We discussed ambient light interferers as one of the challenges when designing an optical system. There is another big challenge to overcome in a reflective-mode optical system, which is called internal light pollution. In a perfectly designed system, all light from the LEDs is sent into the tissue and only reflected light is seen and measured by the photo sensor. In real life, however, LED light can be reflected by the transparent window of the housing and sent back directly to the photo sensor without penetrating the tissue that the light path marked green (seen in Figure 4).

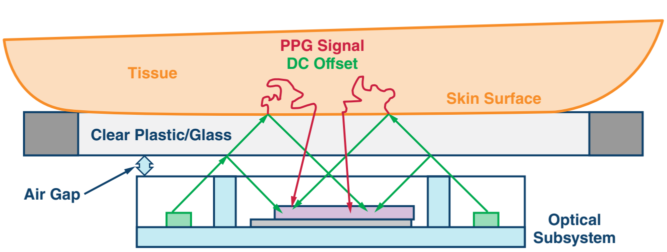

Figure 4. Explanation of internal light pollution.

This ILP effect results in a dc offset and will limit the ac component of the signal, also called modulation index (MI). The MI, in fact, is the only signal we are interested in. ILP can be resolved by separation of the window—however, this is very difficult and costly to implement in volume production. The ADPD174 is the solution to this problem. It has a specially designed housing to reduce the ILP behavior without the requirement for separation of the transparent window in the housing. In Figure 5, improvement is shown on the ADPD174 ILP reduction vs. its predecessor as a function of the LED current. This is another benefit over other discrete or integrated devices that are available on the market.

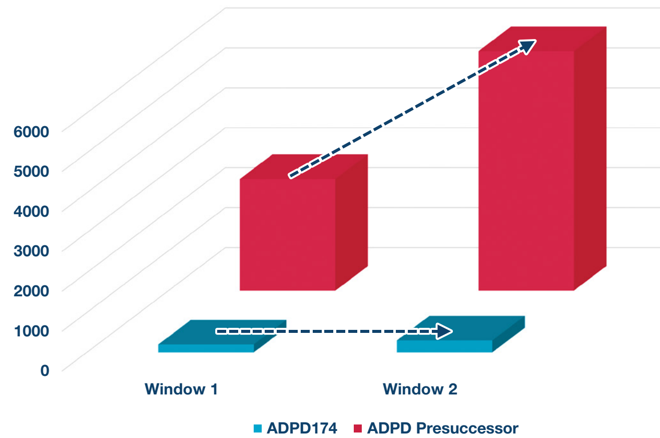

Figure 5. ADPD174 ILP impact vs. its predecessor.

Total Power for Your System

In an optical system, in addition to light interferers, the interference of motion needs to be canceled. Motion has an impact on the overall performance of a wearable system, as due to motion, the mechanical connection or contact to the tissue can get changed, which gives errors in the optical reading. Therefore, it is important to measure the motion of the device and compensate for the interferers. ADI's ultralow power 3-axis ADxL362 MEM's sensor perfectly supports these needs. The sensor measures all three axes and has an integrated 12-bit SAR ADC, resulting in an LSB size of 1 mg and the ability to communicate over a digital SPI interface. The power dissipation scales with the ADC sampling rate and at a data output rate of 100 Hz per axis, the sensor dissipates only 1.8 µA. It is available in a 3 mm × 3 mm package—however, a new generation is in development, using a quarter of the ADxL362 PCB area.

What Is Missing Is the Glue!

So far we have spoken about various sensors needed to build a wearable health device for monitoring heart rate and heart rate variability. What's still missing is the heart of the system, connecting all these sensors together, running the required software algorithms and either store, visualize or transmit the results. The ADuCM3027/ADuCM3029 Cortex®-M3 processor from Analog Devices has recently been announced and is capable of supporting these needs. It is an ultralow power, mixed-signal microcontroller, that consumes < 38 µA per MHz of processing power. The processor has a max clock frequency of 26 MHz and can be operated in four different power modes, see Table 1.

Table 1. Power Modes ADuCM3027/29

ADuCM3027/29 Power Modes
Active < 38 µA/MHz (all analog and digital working)
Flexi < 11.5 µA/MHz (analog active, core clock gated, MCU down)
Hibernate <900 nA (RTC running, wake up interrupts active, SRAM retained)
Shutdown <60 nA (analog/digital in deep sleep, only wake-up interrupts active

The mixed-signal front end includes a 12-bit SAR type ADC, reference buffer, and temperature sensor. There is 128 kB or 256 kB of on-board flash memory, 4 kB of cache memory, and 64 kB of SRAM on board. A lot of effort has been spent in protecting the device content from being read through an external interface by an unauthorized user. This has a huge value to the device manufacturers for protecting their code and algorithms. Finally, the ADuCM302x can be operated from a single operating voltage between 1.8 V and 3.6 V where internally the core voltage of 1.2 V can be generated by either the on-board LDO or its more efficient switch capacitor step-down converter.

For wireless uploading of the measurement results to a host processor, a fair amount of the overall system power is required. Preprocessing the measurement results will help to reduce the amount of data that needs to get transmitted. This brings additional power savings.

Making Your Health Devices Self Learning

In the previous paragraphs, you have learned that ADI has a strong focus on sensor and mixed-signal solutions with the main focus being on performance and low power. These chips and subsystem make it possible to build devices for the health as well as the sports and wellness market, which can operate for a very long time from a single coin cell battery. The challenge is always to build the system with good enough performance at the lowest possible dissipated power. An autoadaptive algorithm can help to improve the overall performance and to find the sweet spot for the power consumption of your system. Each time the device is being used, small changes in the settings can be made to reach the optimal SNR performance and related HRM accuracy for the amount of power spent.

More information can be found at *www.analog.com*.

About the Author

Jan-Hein Broeders is healthcare business development manager for Analog Devices' healthcare business in Europe, Middle East, and Africa. He works very closely with the healthcare industry to translate their present and future requirements into solutions based on Analog Devices market leading linear and data converter technology as well as products for digital signal processing and power. Jan-Hein started in the semiconductor industry 20 years ago as an analog field applications engineer at Burr-Brown, responsible for the Benelux and Scandinavia. Five years after Burr-Brown's acquisition by Texas Instruments, he joined ADI as global FAE for Philips. He has been in his current healthcare role since 2008. He holds a bachelor's degree in electrical engineering from the University of 's-Hertogenbosch, the Netherlands.

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