A New Era in Heart Monitor Technology

Optical Heart Rate Monitor Design

Technologies to record continuous heart rate in an accurate and comfortable way have come a long way over the last several years. People have long relied upon crude measurements taken with a cumbersome heart rate monitor attached by a bulky chest strap. However, the arrival of Optical Heart Rate Monitors or OHRMs with accuracy that matches the "gold standard" chest straps, have now become prevalent.

Advancements in heart rate measurement technology have been driven by the market need for a discreet, accurate, and cost-effective method of measuring heart rate. Technological advances in bio-measurements, electromechanical design, and algorithms have allowed tech firms to overcome the many challenges associated with OHRM measurements. These challenges can be broken into four major categories which include: Biological, Mechanical, Electrical, and Algorithms.

OHRM Measurement Challenges

1. **Biological**: Dark skin, low blood flow (perfusion)
2. **Mechanical**: Interface between device and skin, positioning, optical barrier design, material selection
3. **Electrical**: LED frequency/duty cycle & intensity vs. battery life, photodiode characteristics, AFE bandwidth
4. **Algorithms**: Motion compensation, ambient light filtering

This paper explores each of these challenges and the techniques used to help overcome them in detail.

OHRM is based on a medical diagnostic measurement known as photoplethysmogram (PPG) which involves the use of an emitter to shine light on to the skin and then measuring the transmitted or reflected light with a light sensor. The amount of light sensed correlates directly to the blood volume in the skin, enabling blood flow and heart rate calculations.

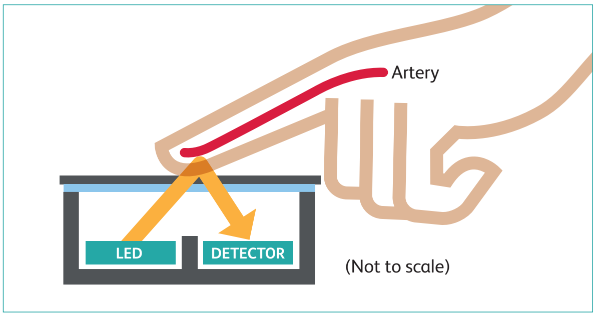

Figure 1. – PPG Measurement

OHRM measurements are essentially a biometric measurement and, as a result, human biological considerations and challenges arise. One such consideration is skin color. Melanin in the skin is a natural light absorber. The darker the skin, the more melanin content it has, the more light it absorbs, and the less reflected light that reaches the light sensor. An effective way to overcome this challenge is to monitor the amount of light that is incident on the sensor and if it reduces below a certain threshold either: A) increase the signal gain of the system and/or B) increase the brightness of the LEDs.

Another less obvious biological characteristic that has a significant impact on OHRM performance is the circulation of blood in the body, or what the medical world calls perfusion. Perfusion can vary drastically across the population and is impacted by health issues including vascular disease and high blood pressure. To further complicate matters, perfusion levels vary across locations on the body. For example, the wrist is notorious for low and unpredictable perfusion, whereas the ear is a more reliable location. Low perfusion results in a low signal and makes it difficult to extract an accurate heart rate. The same techniques used to overcome signal degradation due to dark skin, increase system gain and/or LED brightness, can be used to increase the signal to a level that can be more readily recorded.

In addition to biological challenges, there are a slew of mechanical issues that must be addressed. Maintaining constant contact between the skin and the monitoring device is critical to achieve the primary goal of capturing the maximum level of reflected light. Several mechanical techniques can be employed in this regard:

- Designing a LED/sensor combination that is as close to the skin as possible and secure (not lifting or moving) across use cases;
- Designing a raised surface, or berm, on the back housing to help maintain an interface between the skin and the device;
- Adding ridges around the sensor to give even more assurance that skin contact will be maintained and no ambient light will leak into the optical path and distort the heart rate signal.

Figure 2. – Device Back Housing design

An additional technique is to select a band that is pliable yet maintains its retention. This ensures that the device does not lift off the body during exercise and maintains its form over its lifetime. Popular band materials that achieve these characteristics are elastomer and silicone. These materials are also biocompatible with the human body, thereby minimizing risk of dermatitis and skin rashes.

Until now, the mechanical focus has been on the device exterior. Useful strategies that can be employed to optimize the interior are to select high brightness LEDs, photodiodes with large sensitive areas, and a robust optical barrier between the LED and photodiode that eliminates light leakage. There are tradeoffs however. For example, high brightness LEDs typically lead to higher power consumption, which results in shorter battery life. A larger photodiode comes with additional capacitance which can limit the maximum sampling rate of your system.

Electrical challenges can be mitigated with careful electronic component selection. The major components of a typical OHRM system include the following:

- **Light Emitter & Drive Circuitry**: Typically, a Light Emitting Diode (LED) which is selected for the highest emission at the wavelength of interest. For HR measurements, the color green, with wavelengths between 495nm – 570nm is often used as it is easily absorbed by blood. High brightness LED's should be considered to ensure best signal to noise ratio but this benefit is a trade off with power consumption requirements. Similarly, to save battery life, LEDs should only be kept on long enough to reliably capture the heart rate signal. For these reasons LED Driver control circuitry is needed for intelligent brightness and duty cycle control of the LED.

- **Light Sensor**: Most often a photodiode is used to convert light (incident photons) into current. The photodiode is "tuned" or binned to have the highest sensitivity at the wavelength of interest.

- **Analog Front End (AFE)**: Usually composed of passive noise filtering and a high bandwidth transimpedance amplifier (TIA) to convert the current output of the photodiode to a voltage that can be reliably captured by the Analog to Digital Converter (A/D). The A/D can be a discrete chip or integrated into the system processor.

- **DSP/Algorithms**: Digital Signal Processing (DSP) and algorithms are needed to make sense of the raw data and produce valid heart rate metrics across expected use cases: body type, skin color, device position, indoor/outdoor, exercise, etc.

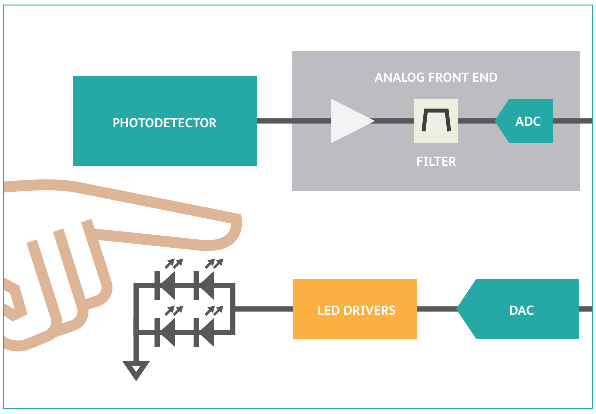

Figure 3. – OHRM Signal Chain

Being able to decipher the raw data that is retrieved from the sensor and translate it into an accurate and dependable heart rate measurement across use cases is a considerable design hurdle. An intelligent and dynamic algorithm is key.

It is a known phenomenon that body motion can couple into a heart rate signal and confuse an algorithm that is not robust. This becomes especially problematic when the motion is repeatable at or near a normal heart rate. The algorithm may lock into the periodic motion signal and produce inaccurate readings. At a basic level the strategy to overcome this issue is to employ an inertial measurement unit (IMU), or an accelerometer, that will capture the motion signal and allow the algorithm to compare and intelligently differentiate between the motion signal and the heart rate signal of interest.

Another challenge is noise generated by ambient light. Irrespective of the care taken to filter the incident light or tune the light sensor to be sensitive only at the wavelength of interest, the sensor will still pick up the ambient light signal. This is because white light contains color across all wavelengths of the visible spectrum. An approach to help overcome this obstacle is to capture the light sensor signal in the absence of the LED light just prior (or directly after) capturing the heart rate signal. This allows the raw ambient light signal to be sampled and a baseline or reference can be developed. Via post processing, the baseline can be subtracted from the composite signal and the heart rate signal of concern extracted.

This paper explored OHRM measurement challenges under four major categories (Biological, Mechanical, Electrical, and Algorithms) and detailed techniques to overcome these hurdles. In the area of biological challenges, two complications that arise are due to dark skin and low blood perfusion, which result in diminished reflected optical signal. Both of these issues can be mitigated with a combination of increased system gain and LED brightness. Mechanical obstacles can be addressed by creating mechanical provisions to ensure maximum contact between the device and the user's skin. This includes placing the LED/sensor combination as close to the skin as possible via thoughtful placement, berm construction, ridge light barriers and careful band selection. Electrical difficulties can be greatly reduced with effective electronic component selection, the most important components being the LED and LED Driver control circuitry, photodiode light sensor, and AFE. Finally, the hardware can only take you so far. A robust algorithm that employs motion compensation and ambient light filtering is necessary to overcome the potential stumbling blocks associated with motion signal cross talk and ambient light interference.

Determining accurate heart rate optically is by no means a simple task. As OHRM technology further advances, the heart rate monitor market will reap the benefits of high accuracy, high uptime OHRM based devices that are noninvasive, affordable, and provide a seamless user experience. The pace of innovation in this space is so rapid that it might just make your heart skip a beat.

About the author

Jason Seitz joined PCH Lime Lab in 2016 where he is a principle hardware engineer. He currently leads electrical engineering from the hardware concept and development phases through to mass production. He has over 15 years of hands on experience leading innovative and pioneering consumer hardware projects at all phases of the product journey. Jason has deep knowledge of wearable technology, including biometric sensors, power management, display, touch and antenna design. He has over seven years of experience developing industrial and medical sensor solutions using a vast array of sensor technology. Jason has published numerous articles on sensor technology and applications for smart health trackers and wearable technology in such publications as EE Times and ECN. He has held lead engineering roles at Intel and Texas Instruments, Inc. Jason holds both an MS degree in electrical engineering from Santa Clara University, and an undergraduate degree in electrical engineering from UC Davis.

About PCH Lime Lab

PCH Lime Lab works with innovative, industry-leading companies of all sizes – established, mid-sized and emerging – who are passionate about design, brand and the consumer experience. We partner as early as the product concept phase to create and deliver unique products and world-class out-of-box customer experiences. Our design engineering is deeply integrated directly into manufacturing and supply chain to reduce risk and optimize speed-to-market. Keeping design integrity, brand and customer expectation at the forefront of our work, we architect elegant and clean solutions and make products based on the desired design, feature set and use case.

With facilities in San Francisco and Shenzhen, China our design engineering team of over 150 mechanical, system architecture (electrical, firmware and software), manufacturing integration, packaging engineers, system integrators and program managers lower the risk of product development and manufacturing, while optimizing quality and delivering exact and reliable engineering. Our customers include: Kodak, L'Óreal, Fitbit, Medtronic, Sonos, among others. PCH Lime Lab is a division of PCH, the world-class, global, 20-year veteran custom product solutions company.

NORTH AMERICA

PCH Lime Lab
PCH Innovation Hub
135 Mississippi St.
San Francisco, CA
94107
USA

ASIA

PCH Lime Lab
PCH Innovation Hub
9A, 9/F, Zhong Tian Yuan Logistics Centre
No. 8, Tao Hua Road
Futian Free Trade Zone, Shenzhen
Guangdong
China

PCH Lime Lab: Rigorous Engineering, When Design Matters.

For more information: Info@Lime-lab.com
pchlime-lab.com | pchintl.com

PCH LIME LAB