AECG100: Empowering PPG Sensor Development and Validation

Introduction

In my role as a sensor application engineer, my primary responsibility within the PPG (Photoplethysmography) sensor system is centered around the design and validation of the hardware components. Additionally, we collaborate closely with our customers, typically device companies, to conduct thorough testing and validation of their hardware, encompassing tasks such as schematic design and PCB (Printed Circuit Board) layout. When it comes to performing functionality tests, particularly those involving heart rate (HR) and SpO_2 (blood oxygen saturation), I would strongly recommend the use of the AECG100. This specific device stands out due to its remarkable flexibility in adjusting PPG waveforms and its efficiency in terms of quick setup.

Now, let's delve into the key testing methodologies for wrist PPG sensors, which play a pivotal role in ensuring the reliability and accuracy of these sensors:

1. **System SNR Testing:** This initial step involves hardware validation, typically focused on evaluating the performance of the analog front-end (AFE). The AFE plays a critical role in controlling the LED driver and ADC conversion, which are vital for accurate PPG measurements. Hardware validation is imperative to ensure that the sensor's Signal-to-Noise Ratio (SNR) aligns with the specifications outlined in the datasheet. To conduct this test, a white or grey card is usually placed atop the PPG sensors, which reflects light from the source to the detector, as depicted in Figure 1 (a). The received data from ADC can be shown in Figure 1 (b).

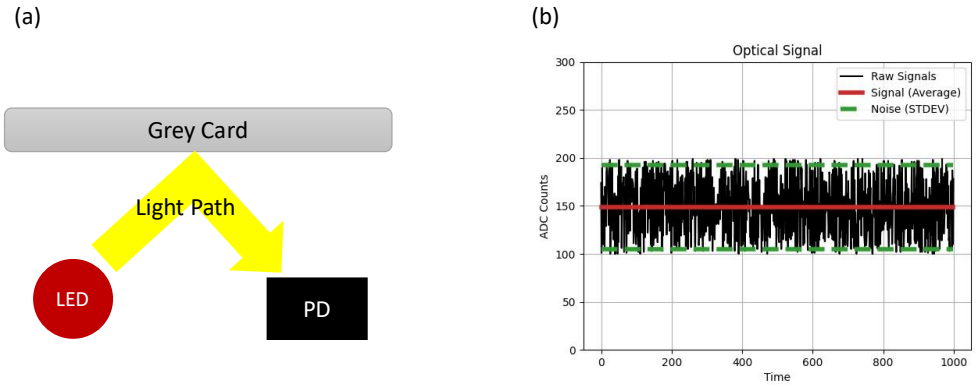

Figure 1. (a) An illustration of a white/grey card setup for SNR testing. (b) The raw data from ADC contains the signal (average) and noise (stdev)

2. **Tissue Phantoms:** While a more time-consuming process, the creation of tissue phantoms involves building an entire system, as no commercial devices are currently available for this purpose. Tissue phantoms are designed to mimic certain biological properties and are employed to test the optical response of PPG sensors. The results obtained from tissue phantom testing are typically compared to in-vivo data from human subjects, serving as a reference to assess the sensor's performance. Volumetric changes in blood flow are typically simulated within the phantom using a pump as shown in many other works [1-3].

3. **PPG Signal Simulator:** This method stands out as one of the most common and efficient approaches. Numerous commercial products are available for generating PPG waveforms and transmitting them through a light source, typically LEDs, toward the detector within the Device Under Test (DUT), often photodiodes (PDs). Volumetric changes, simulating pulsatile signals, are easily created by modulating the intensity of the light source. However, many of the products on the market can only accommodate transmissive based pulse oximeter. AECG100 provides a reflectance-based PPG sensor that allows most of the wearable sensors to be incorporated on the testing setup. Table 1 shows a quick overview of the product comparisons based on the functionalities.
4. **Human Subject Studies:** This phase is crucial in the development of PPG devices, as nearly all products undergo extensive human subject studies to evaluate their performance and validate the device's claims.

While each testing method serves a distinct purpose in the development stage, there are several methodologies that can simplify the testing procedures. Notably, based on my experience with PPG signal simulator tests, I have consistently found that the AECG100 from WhaleTeq is the most optimal choice for functionality and algorithm evaluation tests. Specifically, its SpO_2 functions provide a straightforward and efficient means for developers to validate the hardware, ultimately enhancing the reliability of PPG sensors in various applications.

Table 1. Functionalities comparison of several popular devices on the markets. (Δ means that it is partially working but not completely)

Number	Devices Name	Reflectance based PPG testing	Physiological Functions				Optical Properties			Convenience	
			Heart Rate	SpO2	Respiration Rate	PPG Morphology	DC-only Mode	Multi-Wavelength Response	Optical Power Intensity	Customizable Test	Signal Replay
1	Fluke ProSim 8 with ProSim SPOT	X	V	V	V	X	X	V	X	V	X
2	SpO2 Simulator MS100 Pulse Rate Blood Oxygen Simulator	X	V	V	X	X	X	V	X	V	X
3	BC Biomedical FingerSim™ System	X	V	V	X	X	X	V	X	X	X
4	WhaleTeq AECG100	V	V	V	V	V	V	V	Δ	V	V

Custom Calibration Coefficients for SpO_2

The AECG100 boasts an exceptional feature, its SpO_2 validation capability, which empowers users to customize calibration coefficients for testing their own devices. It's widely acknowledged that not all optical sensor designs are identical, encompassing variations in opto-mechanical design, LED wavelengths, radiation patterns, spectral sensitivity of photodiodes (PD), and field of view. These factors can significantly influence accuracy, coverage, and algorithm development. Optical sensors rely on the absorption coefficients of oxy-hemoglobin and deoxy-hemoglobin at different wavelengths. Consequently, during clinical trials, calibration coefficients can differ based on the specific sensor design.

A common practice involves utilizing two wavelengths around the isosbestic point (approximately 800 nm) [4], one in the red range (600 to 700 nm) and the other in the infrared range (850 to 950 nm), as shown in Figure 2 (a). Through the absorption ratio, typically computed using a first-order fitting of the R value to SpO_2, researchers correlate the data, as depicted in Figure 2 (b). Generating such a graph necessitates numerous clinical trials within a hypoxia lab to validate the device's performance and population coverage.

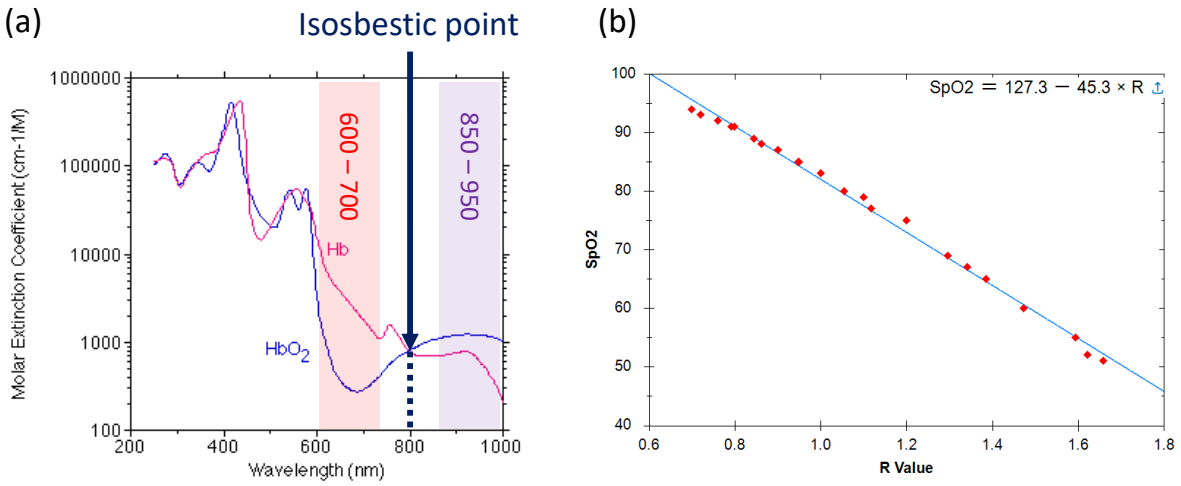

Figure 2. (a) Absorption coefficients of Hb and HbO2 [Adapted from [4]]. (b) A demonstrative fitting curve from AECG software GUI.

Precision in Handling of PPG Waveform Emission

Once users input their own calibration values, the AECG100 emits two waveforms to the photodiode (PD) on the design under test (DUT). Achieving this step, though seemingly straightforward, requires precise operation and a deep understanding of how the PPG Analog Front-End (AFE) functions. To distinguish responses from the two wavelengths, the AFE alternates between turning on one LED and then the other.

LED pulse widths (PW) typically range from tens to hundreds of microseconds in most products on the market. After receiving signals from human tissue, the AFE converts them into digital counts via an Analog-to-Digital Converter (ADC). This digitized waveform is the one typically observed on the monitor, as shown in Figure 3. The AECG100 leverages this process effectively, not only detecting the LED pulse width but also discerning whether the received pulses are in the visible light or infrared spectrum. Subsequently, the device generates corresponding response waveforms based on the entered calibration coefficients, demonstrating its impressive capabilities.

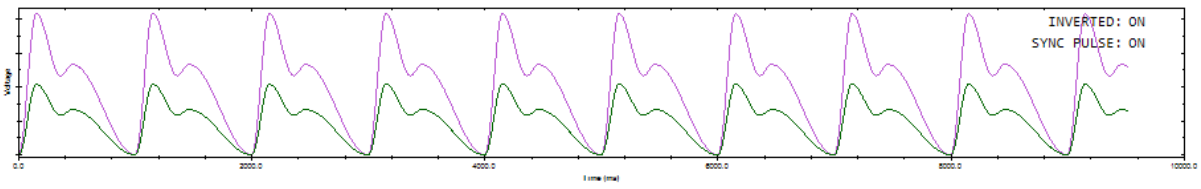

Figure 3. Two PPG waveforms that represent the received signal from red and infrared.

Unveiling Device Secrets: Reverse Engineering Capability

Another remarkable aspect is the ability to evaluate a device on the market for which calibration coefficients are unknown. By observing SpO_2 changes when altering the R value on the device, users can construct their own table of R values. This reverse engineering operation empowers researchers to decipher the inner workings of the device and determine its fitting function of R value to SpO_2. This process not only aids in understanding the device's calibration coefficients but also opens up opportunities for optimization. Researchers can fine-tune their own devices or algorithms by studying the behavior of the unknown device under varying conditions. Additionally, this feature offers a valuable means of benchmarking and competitive analysis, allowing for a more comprehensive assessment of a device's capabilities and performance against industry standards. The AECG100's ability to reverse engineer unknown calibration coefficients thus provides a powerful tool for innovation and advancement in the field of PPG sensor technology.

Enhanced Validation Efficiency: Auto Sequence Feature

AECG100 offers a less commonly seen feature in the market, the auto sequence. This functionality permits users to generate sequences not only for a single heart rate (HR) or SpO_2 value but for a range of different SpO_2 values or HR. For instance, users can simulate a scenario where SpO_2 values shift from 99% to 89% within a 2-minute timeframe, as shown in Figure 4, mimicking a subject experiencing a drop in oxygen levels. If the DUT has an alarm mechanism, this allows testers to assess its responsiveness. While the AECG100 cannot replace essential human trials, it serves as a convenient and cost-effective validation method compared to labor-intensive human subject studies. This additional step empowers developers to fine-tune their designs, ensuring more meaningful and error-free human trials.

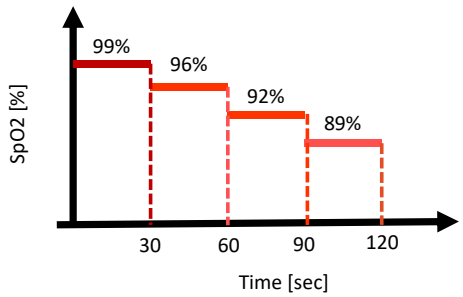

Figure 4. An example of test sequence that can be customized in the AECG 100 for any type of scenarios.

Harnessing Real-World Insights: Data Integration Capability

In addition to its impressive array of features, the AECG100 offers a powerful capability to import real data collected from human subject studies, bringing a dose of real-world practicality to the evaluation process. Imagine you've conducted an extensive human subject study in a controlled environment like a hypoxia lab, meticulously gathering raw PPG waveforms from a diverse group of participants. With the AECG100, you can now take these

authentic waveforms and replay them on a range of devices to assess their SpO_2 algorithm performance.

However, it's important to note that this evaluation may not represent a perfectly fair comparison, as various devices may have different sensor characteristics and processing methods. Consequently, some signal adjustments or reformatting may be necessary to ensure compatibility. Nonetheless, this feature significantly streamlines the evaluation process and facilitates iterative device improvement.

By leveraging real-world data, developers gain a deeper understanding of how their devices perform under conditions that closely mimic actual usage scenarios. This invaluable insight enables fine-tuning and refinement of algorithms, resulting in more accurate and reliable SpO_2 measurements.

Limitations of the AECG100 for PPG Sensor Testing

While the AECG100 is a versatile tool for PPG sensor testing, it's important to acknowledge its limitations to make informed decisions during the development process. I have listed a couple of limitations I noticed:

1. **No Feedback Loop:** The AECG100 lacks a feedback loop, meaning that the LED intensity remains fixed regardless of the detected intensity by the Device Under Test (DUT). This limitation becomes apparent when testing wearable designs equipped with automatic gain control. Such control is essential to ensure that the PD receives a consistent signal across different individuals, meeting algorithm requirements. Without feedback, the AECG100 may not precisely emulate real-world scenarios. The forthcoming WPPG700 is designed to overcome this limitation by adding closed-loop feedback for AGC-related testing.
2. **Lack of Optical Properties:** Unlike tissue phantoms, PPG waveforms emitted by LEDs struggle to simulate complex optical properties like transmissive, scattering, and absorption factors. This limitation is closely related to the absence of a feedback loop, preventing the AECG100 from accurately replicating the interplay of light within biological tissues. Consequently, it may not provide a comprehensive representation of sensor performance.
3. **Fixed Opto-mechanical Design:** The AECG100's fixed opto-mechanical design may pose challenges when attempting to accommodate specific optical configurations. However, users can design custom fixtures, such as 3D-printed light guides, to adapt the AECG100 to their needs. While this flexibility is beneficial, it adds an extra layer of complexity to the setup.
4. **Limited Power Intensity Detection:** Improved resolution in power intensity detection and the recording of detected pulse sequences would be advantageous. Providing users with more detailed information about the intensity of the detected light (e.g., in Watts or received photodiode current) would assist in fine-tuning the AECG100's LED intensity.

5. **Inability to Replace Human Subject Studies:** While the AECG100 offers convenience for functional validation during development stages, it cannot replace the essential role of human subject studies in device validation. Human trials are crucial for assessing real-world performance, user experience, and safety. The AECG100 should be viewed as a valuable tool for initial testing and optimization, complementing rather than replacing human subject studies.

These limitations underscore the importance of a comprehensive testing strategy that combines the strengths of the AECG100 with other validation methods to ensure the accuracy, reliability, and safety of PPG sensors in various applications.

Summary

In the realm of PPG sensor testing, the AECG100 emerges as a powerful and versatile tool, offering a range of functions to streamline hardware validation and algorithm assessment. Its remarkable features include the ability to customize SpO_2 calibration coefficients, simulate diverse PPG waveforms, and create automated sequences for efficient testing. Moreover, it allows the importation of real data from human subject studies, enhancing the understanding of device performance in real-world scenarios.

However, the AECG100 is not without its limitations. It lacks a feedback loop, limiting its ability to replicate dynamic real-world conditions accurately. Additionally, it cannot fully emulate the optical properties of human tissues, which are crucial for real-world testing. The absence of DC signal simulation and fixed opto-mechanical design add further constraints to its utility. Despite these limitations, the AECG100 remains a valuable tool for quick functional validation during the development stages.

What Problems AECG100 Can Solve:

- **Standardized Hardware Validation:** Provides a standardized platform for hardware validation, ensuring the accuracy and reliability of PPG sensors.
- **Customizable Calibration:** Allows customization of SpO_2 calibration coefficients, facilitating tailored testing to accommodate various sensor designs.
- **Efficient Testing Process:** Streamlines testing processes, offering an efficient and cost-effective step to build confidence in device performance before proceeding to labor-intensive human trials.
- **Empowering Developers:** Empowers developers to fine-tune their designs and algorithms, optimizing device performance.
- **Efficient Iterative Development:** Enhances understanding of PPG sensors, reduces development costs, and supports iterative device improvement.

Recommendation

I would highly recommend the AECG100 to other users engaged in PPG sensor development and testing, primarily for its ability to expedite the validation process. Its unique features, such as custom calibration, waveform simulation, and automated sequence generation, offer significant advantages for assessing algorithm performance and hardware reliability. While it may not replace human subject studies, the AECG100 serves as an invaluable tool for initial testing, optimization, and iterative development. By leveraging this device, developers can enhance their understanding of PPG sensors, reduce development costs, and ultimately bring more accurate and reliable devices to market.

Author

Dr. Chin-To “Eric” Hsiao is a biomedical engineer specializing in wearable physiological sensing, multimodal signal processing, and machine learning for non-invasive health monitoring. He received his B.S. and M.S. degrees in Electrical Engineering, where he developed a strong foundation in analog/digital circuit design, embedded systems, and signal processing.

Prior to pursuing academia, Eric spent five years at Maxim Integrated as an Application Engineer, supporting customers in the development and validation of integrated circuit solutions for sensing and wearable applications. His industry experience includes hardware validation, analog front-end characterization, schematic and PCB review, and system-level debugging—experience that continues to inform his practical and translational approach to research.

Eric earned his Ph.D. in Biomedical Engineering from Texas A&M University, where his research focused on advancing medical-grade wearable sensors for cardiovascular and metabolic monitoring. His work integrates photoplethysmography (PPG), bioimpedance, and multimodal sensing with machine learning algorithms to enable non-invasive monitoring of parameters such as SpO_2, blood pressure, cardiac output, and oxygen consumption (VO_2). He has led both human subject and preclinical studies and has published multiple peer-reviewed articles in the field of wearable health technology.

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