Multichannel Module Characterization of Optical Sensors Employed in Photoplethysmography

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Abstract
Photoplethysmography (PPG) is a medical technique using optoelectronic technology to measure blood volume changes in vessels and assess medical condition. The simultaneous multisite PPG measurement has many advantages in assessing various physiological and pathological events related to cardiovascular system. The sensor has a key role in converting the biological signal into electric signal. It mainly comprises of the light emitter and light detector within the preferred red-infrared spectrum. These sensor components have property variations even for identical ones fabricated from the same wafer and in turn may influence the multisite PPG measurement. Different ear and finger sensor pairs with components having specific requirements were considered for the multichannel setup to examine and address the optoelectronic variations. In accordance with that, the designated multichannel sensor module (MCSM) has been developed to connect and power on multiple sensors. It was specified to align intensity variations of the light emitters, reduce their effects and configure almost equivalent conditions in sensor pairs.

1. Introduction
Photoplethysmography (PPG) is a medical technique using optoelectronic sensor to measure blood volume changes in vessels. It is well exploited in pulse oximetry to measure oxygen saturation and heart rate [1]–[4], and has many applications in assessing cardiovascular physiology, risk factors and related diseases [1], [5]–[7]. The PPG system comprises of optical transducer or sensor (input), processing unit (interface and computation) and display device (output). The sensor or probe is the input device conveying the biological signal optically and transforms it into analog (current or voltage) or digital (CMOS or TTL logic pulses) signal. The processing unit usually compounds the electronic circuitry to couple and operate the sensor as well as the computer- or chip-based processor encoded with algorithms to facilitate system control, data conversion, propagation and sampling, digital signal processes and storage. The display unit can be a dedicated monitor to present signals and analyzed results [8].

The PPG hardware is simple to operate and varieties of single- and multi-channel setups have been reported [1], [9]–[12]. The single channel setup is mobile, easy to construct and not costly. The pulse oximeter featuring data recording can be a good alternative to obtain PPG signal. On the other hand, the multichannel setup is meant for swift simultaneous measurement of multiple body sites (2, 4 and 6), better repeatability and accuracy. It offers broader clinical applications to measure physiological responses associated with any medical condition at different and bilateral sites such as ears, fingers, toes and skin. This system is not available off-the-shelf and additional considerations in terms of: design, complexity, effort and cost are required to construct in comparison with the single channel system.

The PPG probe has mainly two optical components: a light emitter in the red-infrared band of 600-950 nm and a light detector in the spectral range of 300-1100 nm, operating in either the reflectance or transmittance mode. The red wavelength range of 600-750 nm is more sensitive to de-oxygenated blood while near infrared wavelength range of 850-950 nm is more towards oxygenated blood. The wavelength of 805 nm is known as the isosbestic point at which the amount of light is similarly absorbed in both oxygenated and de-oxygenated blood [8]. The light emitting diode (LED) has many advances since its invention in the 1960s over the other light sources and becomes the dominant emitter in most chemical analysis and health sensing devices [13]. Similarly the silicon photodiode has become the prominent light detector, also known as photodetector (PD), and have faster and better responsibility to wider spectral range in comparison with its rival the phototransistor [8], [13].

Fig. 1 shows the PPG wave shape in accordance with the blood volume changes in the intravascular space [1], [8]. Once the LED glows on body tissues of the measured site, the incident rays are observed, reflected and transmitted through tissues. Depending on the probe’s operational mode, the attenuated light by reflection or transmission is recognized in PD and the responsivity level is dependent on the LED illumination property as well as the anatomical and physiological properties of the measured tissues [1], [5].

The obtained signal attributes to many characteristic features well investigated in the frequency and time domains for monitoring different stimulants and assessing medical conditions [1], [5], [7]. The PPG applications have coherently emerged in the past few decades coined to the commercialization of pulse oximetry in the 1980s and its widespread use as well as to the technological advancement.
and precision made in optoelectronics. At present, variety of small and sophisticated sensors can be assembled to suit various body segments, anatomy and physiologic as well as wider age groups [1], [8].

The adopted LED in PPG probe is monolithic with narrow peak width operating in the preferred red-infrared color band as mentioned earlier on. The LED current can be either resistor- or IC-based driven and is simply calibrated around the specified current amount to illuminate efficient light beam before reaching the LED saturation boundary. Proper electronic circuitry is required for safely coupling the PPG sensor to any computational unit and minimizing noise and interference to measurement. In a single channel PPG setup, the circuit and connection is compact and can be embedded with the processing unit in one board. However, in a multichannel setup, it is essential to have a separate electronic board for orderly connection, control, operation and troubleshooting due to the fact that there are many system wiring involved. There is also a requirement to provide consistent current drivers for the LEDs of multiple sensors and adjust their unpredictable intensity differences which cannot be avoided even in identical LEDs fabricated within the same wafer. The aim of this work is to develop and construct the pertinent four-channel electronic circuitry and printed circuit board (PCB) for multisite PPG measurement. The board is so-called the multichannel sensor module (MCSM) and should be capable of coupling with different PPG sensor sets under investigation as part of the ongoing four-channel PPG system development. It is worth mentioning that this PPG hardware is intended to simultaneously measure PPGs of bilateral ears, fingers, and toes and assess peripheral responses associated with human physiologic and disorders. However, the scope of this paper mainly focuses on the MCSM development.

2. Methodology

A standalone multichannel PPG system has been proposed using field programmable gate arrays (FPGA) platform as the main computational unit with touch screen LCD monitor [14]. The intention was to connect four sensors and simultaneously acquire biosignals from multiple segments of bilateral peripheries such as left-right ears and fingers. As it is well known that PPG and oximeter probes use similar components and housing fixtures, and hence the off-the-shelf oximeter probes were selected for PPG use. Different sets of two similar ear and two similar finger sensors per set were procured to pick the appropriate combination for the multi-site PPG measurement. The purchased sensors opted two types of PDs with digital output of standard 5V CMOS or TTL level and three types of LEDs (2, 3 and 4 wavelengths) to make 24 available sensor configurations in total, grouped into 6 sets of 4 sensors; each set has 2 pairs of ear and finger sensors. The PDs have similar pin assignments but different responsivity level to red and infrared bands. Though the selected LEDs have 2, 3 and 4 pin assignments with different combinations of red and infrared wavelengths ranging in the 660-940 nm spectrum.

The sensors and configurations considered in this system development have been well addressed in the circuit design of the required MCSM in order to comfortably plug the investigated sensors of different sets and switch pins from one wavelength or sensor configuration to another in a proper manner and with nonfatal errors to measurement, components as well as system. Fig. 2 shows a block diagram of the designated PPG setup and the main components and subsystems required to develop this system. This study has been endorsed by the Research Ethics Committee of Universiti Kebangsaan Malaysia Medical Center.

![Block diagram of PPG system including main circuits of the multichannel sensor module](image)

Fig. 2 Block diagram of PPG system including main circuits of the multichannel sensor module

The MCSM has been designed as a control panel supporting different sensor arrays and configurations for safe and reliable signal propagation and computation within the processing unit. It has mainly two simple circuits one for PD array and another for LED array. The PD circuit was intended to power multiple detectors and forward light intensity variations represented in TTL pulses to the computational unit where the output biosignals or PPGs of multiple sensors are acquired using digital counters and segmented at equal sampling intervals for further processing and analysis. On the other hand the multiple LEDs were circuited in a way to be either resistor- or IC-based current driven. The appropriate tracks for the IC-based current drive have been channeled with the processing unit for providing the necessary signals and clocks to operate the IC chip, select the designated LEDs and control their intensity levels. With resistor current drive, the intensity levels of LEDs are manually calibrated using individual variable resistors. Using processor-based port-enabling subsystem, the number of channels is opted via the PD output pins to allow single or multiple site measurement as shown Fig. 2.

The sensors come with a 3 m long shielded cable each and have either 6-pin or 7-pin male-round connector to plug with their dedicated machine female connectors mounted on the PPG hardware. The machine connectors are internally wired to MCSM through separate PD and LED connectors. Fig. 3 shows the constructed 2-layer MCSM with width-height dimensions of 105 and 65 mm respectively and 4 padding holes to fit properly in the space allocated inside the PPG hardware. There are two 2-pin power connectors of P1 and P15 to supply 5 and 3.3 V DC respectively. The one way 13-pin connector of P6 links MCSM with the processor unit to provide the required signals for the IC chip (U1) and propagate the PPG signals for further processing. It is also dedicated to reassign LEDs with U1 if IC-based current drivers were to be employed.

The PD circuit was assigned with four 3-pin connectors of P2-5 to simultaneously operate the PDs of both types and
similar pin assignments. The PD connectors have each two pins for power (0 and 5 V DC) and a third pin for PD output representing the PPG signal. All four PD output pins were connected to P6 and from P6 to four I/O pins enabled for inputting PPG signals to processor subsystems (Fig. 2). Both PD types generate 5V TTL output which is higher than that of the processor’s I/O pins, and hence four voltage dividers were constructed for reducing voltage to 3.3 V before crossing over to the dedicated I/O pins in the processor. Four sets were required to install the 4 potential dividers; each to have two resistors of 2.2 kΩ (R1-4) and 4.7 kΩ (R5-8).

PCB module of the specified dimensions. The width of the power tracks of 0, 3.3 and 5 V was made double than that of data tracks. All tracks in PCB layers were checked for any route constraints. The Gerber files were then generated for printing the circuit board. The constructed module PCB was fitted with all electronic components and properly mounted in PPG system. All connectors of power, data, LEDs and PDs were properly installed and resistor current drivers were set as per specified LED wavelength. With these connections and settings in place, the MCSM was ready for acquiring the PPG signals from multiple body peripheries.

3. Results
In this paper, a single set of 4 sensors (2 ears, S1, and S2, and 2 fingers, S3 and S4) was inspected out of the six sensor sets. All sensors were medically-certified transmittance-type and normally having similar types of PDs and LEDs in the set. The selected LEDs were 2-wavelength type ELM-4003 (Measurement Specialists Inc.) whereas the digital PDs were type TSL235R (TAOS Inc.). The sensor pairs were assembled with the appropriate ear and finger clip fixtures to fit properly on earlobes and index fingers respectively. All of them were made with soft 3m cable and terminated with 6-pin round connectors. The reported single-channel sensor module (SCSM) of PPG system [15] has been modified with a fixed resistor of 110 Ω to drive the LED red color (660 nm) above 20 mA. This system was used to provide a fixed and sole setup to test and compare the PD responsivity or intensity level of all sensors. The data output of each PD is a train of pulses at fixed level of 5 V (TTL logic) but with variable widths influenced by the transmitted light from tissues. The pulses train propagated the system through a 16-bit digital counter at a sampling rate of 1 kHz and the recording time is about 2 minutes for all sessions. The set was scheduled to have three tests: first to measure intensity level (I) of individual sensors, second to measure (I) before and after adjusting the resistor current drive to obtain equal intensity level for the ear and finger sensor pairs and third to determine the ear and finger PDGs after intensity adjustment.

The light intensity measurement of all sensors was taken in free airspace, i.e. sensors not clipped on measurement site. They were isolated from ambient light (noise) by wrapping them with an opaque black plastic bag. The black color also helps to minimize the reflection of red beam internally. The covered sensors were connected one at a time to the SCSM for separately measuring their maximum intensity level. The intensity variations were determined by counting pulses of the digital counter at equal increments and the obtained samples were integers in arbitrary unit (au). The recording sessions were repeated three times for each sensor to enforce repeatability and data were analyzed using the standard statistical tests out of the three sessions as illustrated in Table I. The intensity variations (Imin-Imax) in left ear sensor (29 au) are quite high in comparison with right ear sensor (13 au) and both are higher than that of the finger sensor pair (<5 au). Interestingly the Imed for the ear sensor pair was similar and with small difference in Imed while these values were obvious, about 24 au in both Imed and Imax, between the sensors of the finger pair.
Table I Intensity variations (au) in identical ear and finger sensor pairs using the same SCBM and fixed resistor to drive the LED red light and acquired data samples at 1 kHz

<table>
<thead>
<tr>
<th>Sensor</th>
<th>R (Ω)</th>
<th>I_{min}</th>
<th>I_{max}</th>
<th>I_{mdn}</th>
<th>I_{mdn}</th>
<th>I_{dat}</th>
</tr>
</thead>
<tbody>
<tr>
<td>S_{lf}</td>
<td>110</td>
<td>422</td>
<td>451</td>
<td>433</td>
<td>435</td>
<td>3.95</td>
</tr>
<tr>
<td>S_{rf}</td>
<td>110</td>
<td>424</td>
<td>437</td>
<td>433</td>
<td>431</td>
<td>0.53</td>
</tr>
<tr>
<td>S_{lf}</td>
<td>110</td>
<td>138</td>
<td>143</td>
<td>142</td>
<td>142</td>
<td>0.10</td>
</tr>
<tr>
<td>S_{rf}</td>
<td>110</td>
<td>163</td>
<td>167</td>
<td>166</td>
<td>166</td>
<td>0.06</td>
</tr>
</tbody>
</table>

The constructed MCSM board was then installed with all sensors and power connectors. The jumpers of P11-14 were configured to connect and illuminate the LED red light in all sensors. The resistor trimmers of all channels were initially configured to 111±3 Ω to test intensity variations with similar resistor current drivers. The intensity levels were recorded using SCBM by sequentially plugging PD output pin from one channel to another with the SCBM 16-bit counter. Similarly the sensors were isolated from ambient noise by using black plastic bags and the intensity variations were again measured in free airspace. Data were recorded for a single session per sensor and median intensities (I_{mdn}) were calculated as 362, 297, 163 and 194 au for the left-right ear and finger sensors respectively and in this time the intensity differences in both sensor pairs were obvious.

In the next test, the resistances were adjusted while observing PD outputs until approximately equal intensity detected in the sensor pairs. The intensity levels of all sensors were again measured sequentially for three sessions and the statistics of this test are illustrated in Table II. After R adjustment, the I_{min}-I_{max} differences in ear and finger pairs were about 29 au and 5 au respectively. The I_{mdn} of ear pair were reduced to differ by about 5 au while the same value was obtained in the finger sensor pair, and hence improved intensity levels in pairs were achieved after adjusting the resistances.

Table II Similar intensity levels in identical ear and finger sensor pairs obtained using the constructed MCSM PCB after resistance adjustment and data samples acquired sequentially using SCBM

<table>
<thead>
<tr>
<th>Sensor</th>
<th>R (Ω)</th>
<th>I_{min}</th>
<th>I_{max}</th>
<th>I_{mdn}</th>
<th>I_{mdn}</th>
<th>I_{dat}</th>
</tr>
</thead>
<tbody>
<tr>
<td>S_{lf}</td>
<td>111</td>
<td>209</td>
<td>327</td>
<td>302</td>
<td>305</td>
<td>0.27</td>
</tr>
<tr>
<td>S_{rf}</td>
<td>205</td>
<td>291</td>
<td>327</td>
<td>307</td>
<td>307</td>
<td>0.48</td>
</tr>
<tr>
<td>S_{lf}</td>
<td>168</td>
<td>159</td>
<td>164</td>
<td>162</td>
<td>162</td>
<td>0.02</td>
</tr>
<tr>
<td>S_{rf}</td>
<td>98</td>
<td>158</td>
<td>164</td>
<td>161</td>
<td>161</td>
<td>0.02</td>
</tr>
</tbody>
</table>

In the final test and while the sensors were connected to MCSM board and powered on, the sensor pairs were clipped properly on a voluntary non-symptomized subject to measure PPGs of the bilateral earlobes and index fingers in sitting position. Despite operating the sensors simultaneously, the data recording was not simultaneous, performed using the 16-bit counter of SCSM and samples of sensors were acquired at 1 kHz successively in a similar manner to the previous test setup. Fig. 4 depicts the processed PPGs after applying the common bandpass range of 0.5-10 Hz and removing the non-pulsatile components.

The multiple sensors have obtained analytical PPGs of the bilateral peripheries though the further signal processing is beyond the scope of this paper. Further inspection of the other sensor sets using both resistor- and IC-based current drives should be scheduled to identify the reliable driver for obtaining consistent light intensity in all sensors.

4. Discussions

The new MCSM board was constructed with simple circuitry and switching mechanism to facilitate the connection of different sensor sets having various pin assignments and connectors. The 4-pin LED and 3-pin PD junctions have been fitted per channel and they are considered sufficient to employ variety of LEDs and PDs for this type of sensors without requiring additional circuit or board modification. The resistor- and IC-based current drivers are common circuits alternatively used in controlling LED illumination. The IC-based of single output can be an alternative current drive for the individual LEDs instead of array current driver of TLC5917 used in MCSM. If single output IC-based current drive were to be used then take into considerations the size and space of the individual circuits required on PCB for the four channels.

The four 2-way 8-pin connectors were fitted as switches for changing LEDs from one wavelength to another. There were only two jumpers supplied per switch to ensure that only one LED light is wired and in turn avoid damage to LED, PCB or system as well as error in measurement. The alternative 2-way 8-pin 0/1 (or on/off) switch can be a more presentable junction type nonetheless it is more prone to mistakes by having more than two pins or paths activated (i.e. switched on) at a time. Hence there is higher possibility of setting LED leads wrongly or more than one light switched on, which may in turn cause unstable measurement as well as system defects.

The variable resistors or trimmers play essential role in aligning the intensity level for all sensors. Despite their higher tolerances noticed in comparison with fixed resistors they have given the flexibility and control to swiftly change resistance for LEDs and reduce the intensity differences in ear and finger sensor pairs to about 5 and 0 au respectively. Similar procedure should be scheduled to test the infrared wavelength of this set’s LEDs in terms of intensity differences and PPG features followed for the other sets. The max-min intensity differences for ear sensors were recorded quite high to that of finger sensors. There is no handy explanation for this and further investigation is required. The use of IC-based current drive may be a good solution. It is worth mentioning that the fixed resistor has had one incident where equal intensity level obtained in the ear sensor pair as
illustrated in Table I while the same pair was showing differences in readings when calibrated in MCSM. The calibration of ear sensor pair connected to SC SM was repeated for a few times and intensity level continued to be the same. Again further investigation should be conducted for explaining this very occasional incident.

This paper has presented a method for calibrating LED illumination based on the output of identical PDs. The calibration of PD responsivity and sensitivity of light has equal importance in PPG measurement. This justifies why sensor sets were procured with PDs having different sensitivity level to wavelengths within the red-infrared spectrum so that the intensity level can be thoroughly investigated with respect to PDs as well for obtaining good analytical PPGs out of the bilateral peripheries. The good thing about the different PDs selected for this work is that they came with similar pin assignment, and hence the MCSM board should still be valid for operating both designated PDs as well as any new ones as long as they have similar configuration of 3 pins and digital/TTL output. Furthermore the MCSM board can be used for multichannel pulse oximetry though additional LED switching circuitry will be required for signaling the red and infrared lights alternatively. Though it may be limited for use with analog PD unless the potential dividers made for each channel is isolated and the PD output is bridged to analog-to-digital converter (ADC) circuit prior to propagate the digital counter of the processing unit.

5. Conclusions

The MCSM board has been fabricated to nicely mount and couple with four sensors for multisite PPG measurement. It can reliably adopt the different sensor sets procured for this work using the same circuitry and junctions with minimum intervention required in configuring switches and trimmers. The surface mount 500 Ω trimmers were necessary to fine tune the resistor-based current drive to reduce intensity differences between the pairs of ear and sensors. Additionally the IC chip of constant current drivers for LED array was also incorporated and connected with the appropriate operational signals should the IC-based current drive be desired. We believe that the calibration technique used here is an essential approach for inspecting and troubleshooting PPG sensors employed in any multichannel setup. We suggest that this technique should be organized next for validating the other sensor sets and also investigating the designated sensitivity out of the different PDs as well as identifying the sensor set that is more suitable for PPG measurement.

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References


