

# Ultra-low power photoplethysmography $SpO_2$ measuring techniques

C. Barriuso Medrano, J. Calpe Maravilla, C. Millán Navarro

Analog Devices, PCUV, C/ Catedrático Agustín Escardino, 6, Paterna, Valencia, Spain

## Abstract

*Photoplethysmograph(y) (PPG) is widely used to obtain vital signs such as the peripheral capillary oxygen saturation ( $SpO_2$ ) or the heart rate (HR) non-invasively in real time. These techniques require a great amount of power in order to obtain reliable data, and its use is limited to mains powered devices. For this reason it is of great importance to find methods and algorithms that reduce its current consumption. Three techniques to optimize current consumption when obtaining PPG signals in order to obtain  $SpO_2$  and heart rate (HR) are proposed in this study. Each of them takes advantage of the fact that to obtain these vital signs we only need the peaks of the PPG signal, which means that we may change the accuracy of the acquisition depending on the position within the pulse. The current consumption can be reduced by 55% in the sensor and 62% in the microcontroller.*

## 1. Introduction

Body monitoring provides valuable information that properly conditioned can be used to obtain vital signs. Photoplethysmography is a technology that has been used for decades to obtain HR,  $SpO_2$  or the breathing pace. It is a method that consists in measuring changes in the volume of a certain area of the body's limb using light. This volume will change with the heart beat so that when no blood is flowing through the capillaries it will be small compared to when blood is flowing. PPG works by pushing light pulses towards the skin and measuring the diffused light that has travelled through the tissues of the skin. The amount of light received will depend among other factors on the volume of the capillaries. HR can be obtained either by measuring the peak to peak time or by signal periodicity analysis.

By obtaining two PPG signals using two different wavelengths,  $SpO_2$  can be obtained as can be deduced thanks to the Beer-Lambert's law [1,2]. This deduction establishes a relationship between the amplitude of the peaks of the PPG signals and the actual  $SpO_2$  value.

In order to obtain these vital signs we only need the peaks of the PPG signals. Therefore the smartest approach is to sample the signal applying more power in the zones around the peaks whereas in the rest of the signal we can save power by reducing the sampling accuracy.

The aim of this study is to determine if the current consumption of  $SpO_2$  and HR measurements using PPG can be optimized. Along the work a multi-purpose PPG signal measuring system was developed [3-5] using the Analog Devices ADPD144 sensor along with an ST

Cortex-M4 microcontroller to interface with the sensor that can change the configuration of the measurement to put into practice the power reduction techniques

## 2. Power reduction algorithms

In order to reduce the power consumption three algorithms are proposed. They change the sampling configuration depending on the position of the PPG signal (Peak or slope). We will difference between the High Performance Acquisition Period (HPAP), i.e. the peak zones, and Low Performance Acquisition Period (LPAP), i.e. the slopes. When changing the acquisition period type a different configuration will be sent to the sensor depending on the algorithm.

The sensor that has been used in this project, the ADPD144, offers a wide variety of configurations. We can set two different time slots for each sample, each of which can have a different configuration. Each slot controls its own LED and photodiode, which means that we can measure PPG signal with two different LEDs at different wavelengths. The sampling frequency is configurable, as well as the current pushed to the LEDs and the number of pulses averaged in each sample. Indeed, instead of sending a DC constant current to the LEDs, a configurable number of pulses are sent and averaged before sampling. This allows a better rejection of ambient light and helps to reduce the current consumption.

The algorithms described below are shown in Figure 1.

### 2.1. Pulses algorithm

This approach changes the number of pulses sent to the LEDs that will be averaged for each sample depending on the zone of the PPG signal. In the HPAP several pulses can be sent to improve signal quality whereas in the LPAP just one pulse is sent in order to reduce the current consumption while getting a coarse reading.

The drawback of this algorithm is the noise the PPG signal will show in the LPAP, as there will be no average as in the HPAP.

### 2.2. Start/Stop algorithm

The aim of this algorithm is to reduce the current consumption by completely switching off the sensor in the LPAP. This is the most aggressive approach and it will be the one that will save more current.

The main drawback of this algorithm is the probability of losing a peak. If the peak estimation algorithm does not

predict correctly where the next peak will take place, the sensor may be turned off in a peak zone, losing this way the peak. This scenario can happen in patients with large HRV or in an inadequate measuring environment, where additional noise can distort the PPG signal

### 2.3. Sampling frequency algorithm (Fs)

The proposal of this algorithm is to dynamically change the sampling frequency depending on the position of the PPG signal. This way the signal will be sampled with a high Fs in the HPAP and with a low Fs in the LPAP. This seems to be the most sensible approach. Peaks will not get lost as long as the LPAP Fs is acceptable. Moreover the signal will not be noisier as in the pulses algorithm.

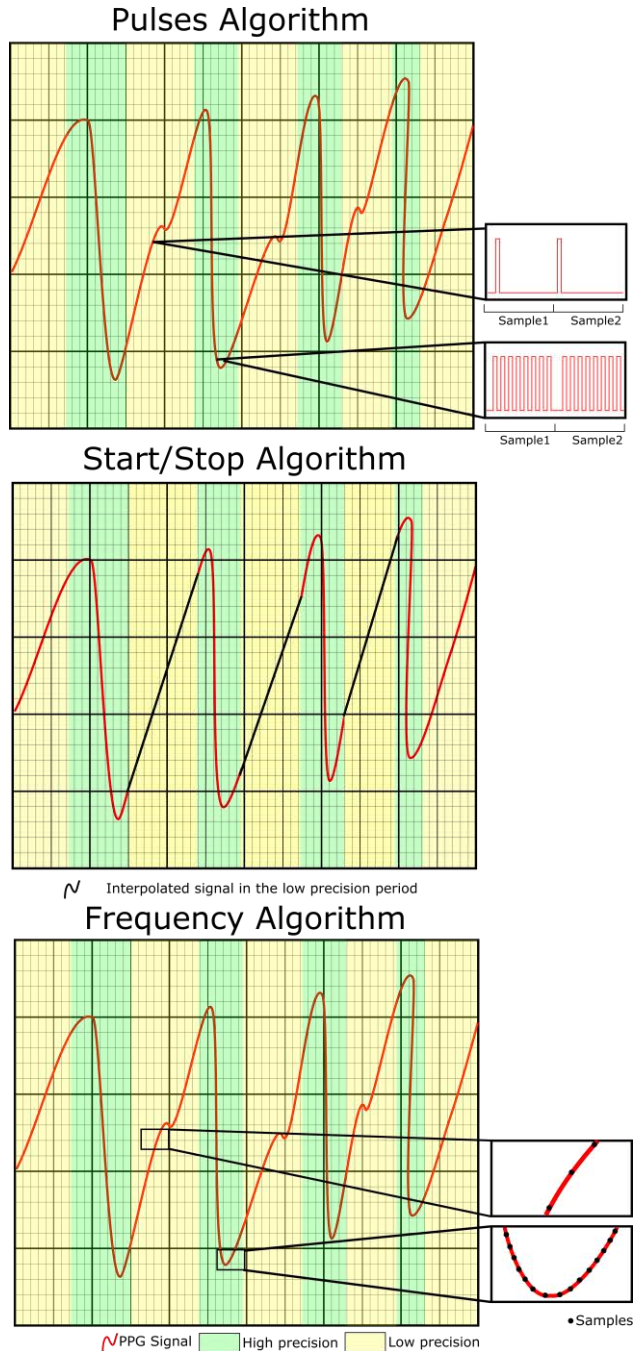


Figure 1. Proposed current reduction algorithms

### 3. Signal filtering

Before actually applying these algorithms we must identify the PPG signal peaks. In order to obtain these peaks a custom filter has been designed. Filtering the PPG signal has to meet some requirements. It has to have a linear phase so that the group delay is constant. This group delay has to be kept as small as possible so that we can run the algorithms in real time. Moreover the filter has to reject the signal noise as well as the dicrotic notch as this can be misunderstood as a regular peak. Last but not least the coefficients of the filter should be integers so that filtering does not take too long.

The designed filter is a combination of a comb filter and a moving average filter. It has been designed as a band-pass filter around the frequencies of the heart rate: 0.66 Hz for 40bpm and 3.7 Hz for 220bpm. The moving average filter will get rid of the signal noise, as it is a LPF. The comb filter will apply a derivative to the resulting signal, giving this way the location of the original signal peaks in the zero crosses. Taking into account the group delay of the filter we will be able to locate the peaks in the original signal.

The notches of these filters are located at:

$$f_{notch,comb} = k \frac{f_s}{N} \quad \forall k \in \mathbb{N}$$

$$f_{notch,movAvg} = k \frac{f_s}{M} \quad \forall k \in \mathbb{N} - \{0\}$$

For a comb filter with N+1 coefficients and a moving average filter with M coefficients:

Index	0	1	...	N-1	N
Comb	1	0		0	-1

Table 1. Comb filter numerator coefficients

Index	0	1	...	M-1
Mov.Avg.	1	1		1

Table 2. Mov.Avg. filter numerator coefficients

Applying this filter to the original signal will return a signal in which zero-crosses represent signal peaks delayed and the slope of the filtered signal at that point will determine if the peak is a local maximum or a local minimum. The total filter is shown in Figure 2.

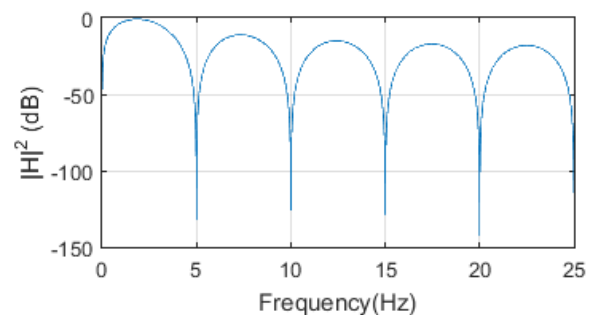


Figure 2. Total filter magnitude

#### 4. Peak estimation

After filtering the signal we will locate the peaks. To put into practice the algorithms explained in Section 2 we have to estimate where the next peak will take place. At the beginning of each heart rate period this estimation is obtained so that we can set the LPAP configuration at the desired percentage of the current heart period and go back to the HPAP at a certain percentage as well.

In order to estimate the next peak the previous 10 peak to peak periods are taken into account. They may be weighted so that the most recent periods are more representative than the older ones. Several weighting methods were tested: equal weighting, linear weighting and exponential weighting. We concluded that the one that showed better results was the linear weighing estimator. For this reason, in order to determine where the next peak will take place we use this formula:

$$Peak_{i+1} = Peak_i + \frac{\sum_{j=0}^9 (10-j)(Peak_{i-j} - Peak_{i-j-1})}{45}$$

#### 5. Signal conditioning

The algorithms explained in Section 2 modify the ideal PPG signal in order to reduce current consumption. The start/stop algorithm will turn off the sensor during the LPAP, and therefore we will not have samples for that period of time. On the other hand the Fs algorithm will change the number of samples received per second in the LPAP. Finally, the pulses algorithm will return the PPG signal attenuated in the LPAP as we are integrating less pulses.

As filtering requires the input signal to have the same sampling characteristics along the measurement, we will have to condition the incoming signal from the sensor so that it can be filtered. Depending on the algorithm we will modify the signal in a different way. In the Start/Stop algorithm we will interpolate the samples we have not obtained. We will create a slope between the last sample obtained in the previous HPAP and the new sample of the new HPAP. When it comes to the Fs algorithm, we will have to interpolate the signal in the LPAP so that it has the same sampling frequency as in the HPAP. We will apply a linear interpolation in this case. Finally, in the pulses algorithm we will normalize the signal to the number of pulses sent in the HPAP so that the LPAP has the same average value.

This way the filter will work as expected, filtering this PPG signal with constant Fs and shape.

#### 6. Current consumption evaluation

It is necessary to differentiate between the current consumption of the microcontroller and the current consumption of the sensor (including the LEDs). The created algorithms will reduce the consumption of the sensor, however they may increase the consumption of the microcontroller under certain circumstances. This is because the microcontroller will have to face the extra processing load of the algorithms. Nevertheless we have to take into account that with the Start/Stop and the Fs

algorithms less samples are obtained and therefore the consumption of the microcontroller will be reduced as well.

##### 6.1. Measuring the consumption of the sensor

The sensor we have used for this study has two different supply lines. One of them is used in the sampling and ADC stage and the other one feeds the LEDs. For this reason two separate consumptions were measured, one for each line. Two 1  $\Omega$  sensing resistors were introduced in the supply lines. These two resistors will provoke a voltage drop depending on the current flowing. This voltage drop however will be rather small, and for this reason we will need two instrumentation amplifiers with its inputs hooked to the terminals of the resistors to magnify the voltage drop. This way we will obtain the average current consumption of each line.

##### 6.2. Measuring the consumption of the microcontroller

In order to obtain the consumption of the microcontroller an estimation will be used. The average time of the power reduction algorithms will be measured. With this figure and the average consumption of the microcontroller provided by the manufacturer we will obtain the total average consumption. We will take into account that the microcontroller sleeps in the time periods in which it is not processing.

#### 7. Results

We will separate the current consumption of the sensor and the microcontroller

##### 7.1. Sensor consumption results

To obtain these results, each algorithm was run 10 times for 10 seconds. The consumption of the sensor was obtained as well, so that we can calculate the reduction percentage that can be achieved with these algorithms.

Algorithm	LPAP Cfg	% Reduction	Mean (mA)
None	8 Pulses	0	2.4
	200 Hz		
	ODR		
Pulses	400 Hz Fs	36	1.57
	1 Pulse		
	200 Hz		
Fs	ODR	39	1.47
	400 Hz Fs		
	8 Pulses		
Fs	50Hz ODR	48	1.25
	100Hz Fs		
	8 Pulses		
Fs	50Hz Fs	51	1.18
	8 Pulses		
	25Hz ODR		
Start/Stop	25Hz Fs	52	1.16
	-		

*Table 3. Current consumption of the sensor*

These results were obtained for a subject with a 60bpm mean heart rate. The LPAP was configured to start at 30% of the estimated beat to beat period, and to stop at 85%.

## 7.2. Microcontroller consumption results

The consumption of the microcontroller was estimated as explained in Section 6.2. With this information and the average consumption of the microcontroller in the active mode (40mA) and in sleep mode (390uA) we can calculate the average current consumption of the microcontroller with the algorithms. Several factors have to be taken into account when estimating the consumption. One of them is the execution time of the algorithms that is shown in Table 4.

Algorithm	Pulses	Start/Stop	Fs
Time ( $\mu$ s)	376.2	379.3	376.1

Table 4. Execution time of the algorithms

Another important factor is the depending on the heart rate. We will not always be able to start the LPAP period as desired due to the group delay of the filter. This is because the maximum peak will not be detected on time. This scenario usually happens when the HR is higher than 90 bpm. For this reason the microcontroller consumption will depend on the heart rate as well. In Figure 3 the average microcontroller consumption has been plotted.

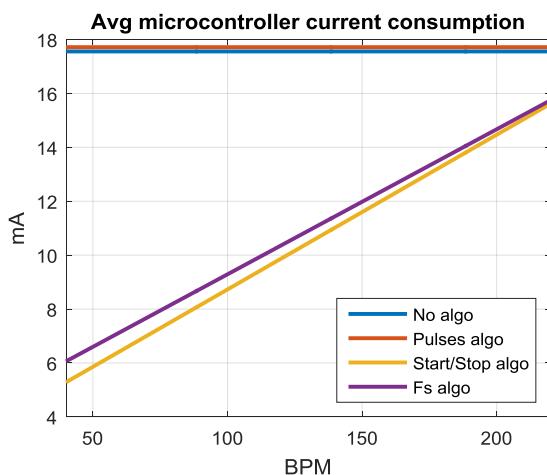


Figure 3. Average microcontroller consumption

As we can see in Figure 3 the current consumption with the algorithms running can be reduced in the Start/Stop and in the Fs algorithms. This is because the processor has to obtain less number of samples from the sensor, current. The current consumption that can be saved with the Start/Stop algorithm for a heart rate of 60bpm is 11mA for this microcontroller, which means a 62.6% current reduction in the microcontroller. As we can see, the achievable current reduction with the Fs algorithm is almost the same. This is because the Fs in the LPAP period is relatively low (25Hz) and therefore the current consumption drops.

## 8. Conclusion

Three algorithms have been proposed to reduce the current consumption when obtaining vital signs such as HR or  $SpO_2$  using PPG techniques. These techniques take advantage of the fact that we only need the peaks of the PPG signal to obtain these vital signs. These algorithms change the sampling configuration depending on the position within the PPG signal.

We have concluded that it is possible to implement these algorithms in real time, and therefore it is possible to reduce the current consumption of the overall system. The achievable current reduction in the ADPD144 photometric sensor that has been used in this project is 52% using the Start/Stop algorithm. When it comes to the microcontroller the current reduction will depend on the heart rate, however we can achieve a 62.6% of current reduction with an average 60bpm HR.

The algorithm that performs better is the Fs algorithm and therefore is the recommended one. It changes the sampling frequency depending on the location of the PPG signal, however it is always sampling. For this reason the measurement will be more reliable compared to the Start/Stop algorithm. This last one can perform poorly if the peak estimation does not work properly as a consequence of a great HRV or an excessive measurement noise. Lastly, the pulses algorithm performs fine, however the current that can be saved with this algorithm is not as high as with the other two.

Finally, the three algorithms perform properly on subjects with normal HRV. No  $SpO_2$  or HR degradation has been observed along the tests carried out. These techniques suit applications in which these vital signs can be obtained coarsely.

## 9. Acknowledgements

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## 10. References

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