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A Flexible-Window Filtering Technique for Interference Suppression in SpO2 Monitoring

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***Abstract*—The peripheral oxygen saturation (SpO2) reflects the metabolic capacity of the human body, which can be used in assessing or screening symptoms such as pulmonary embolism. Photoplethysmography (PPG) is a common method for SpO2 monitoring, while it suffers from interferences such as ambient light scattering, reflections, and motion artifacts. These interferences significantly degrade the accuracy of SpO2 monitoring. Filtering techniques are widely used to suppress the interferences in PPG signals. However, conventional PPG filtering techniques use a fixed window, which is not able to handle interferences at different frequencies. In this paper, we propose a flexible-window filtering technique to suppress the interferences in SpO2 monitoring. To validate the proposed technique, we built a prototype to monitor the in-vivo SpO2 of the human body. Measurement results show that the proposed technique reduces the mean absolute percentage error (MAPE) of SpO2 by 46% compared to the conventional methods.**

***Keywords*—peripheral oxygen saturation (SpO2); photoplethysmography (PPG); interference; mean absolute percentage error (MAPE); filtering**

I. Introduction

Peripheral oxygen saturation (SpO2) measures the percentage of oxygen binding sites in the blood, which is a significant physiological indicator in hypoxemia [1], acute heart failure [2], lower extremity arterial disease [3] and chronic obstructive pulmonary disease [4]. The SpO2 can be collected utilizing a pulse oximeter non-invasively. The pulse oximeter uses light sources with different wavelengths to get the photoplethysmography (PPG) signal, where the SpO2 value can be calculated based on the Beer–Lambert's law [5]:

$$SpO_2 = 110 - 25\frac{V_{ac1}/V_{dc1}}{V_{ac2}/V_{dc2}}, \tag{1}$$

where V_{ac1} and V_{dc1} are the AC and DC components of the PPG signals in red light, V_{ac2} and V_{dc2} are the AC and DC components of the PPG signals in infrared light, respectively. However, pulse oximeter measurements are generally sensitive to interferences such as ambient light scattering, reflections, and motion artifacts. These interferences affect PPG measurements and thus degrade the accuracy of SpO2. Therefore, it is essential to suppress these interferences in SpO2 monitoring.

PPG filtering techniques have been introduced in previous works to mitigate the effects of interferences, including time-frequency reconstruction [6], independent component analysis (ICA) [7], and least means square (LMS) adaptive filtering [8]. These methods usually utilize a fixed-window for time or frequency spectrum analysis. However, the fixed-window method is not able to handle all the interferences appearing in an arbitrary time slot or frequency band. As a result, a reference signal such as isosbestic wavelength light (with the same light absorbance of red and infrared red light) [9], acceleration [10], synthetically construction [11] is usually adopted to reject the interferences. However, in order to generate reference, additional hardware such as light source [9] and accelerometer [10] are required, which increases both the volume and power consumption of the system.

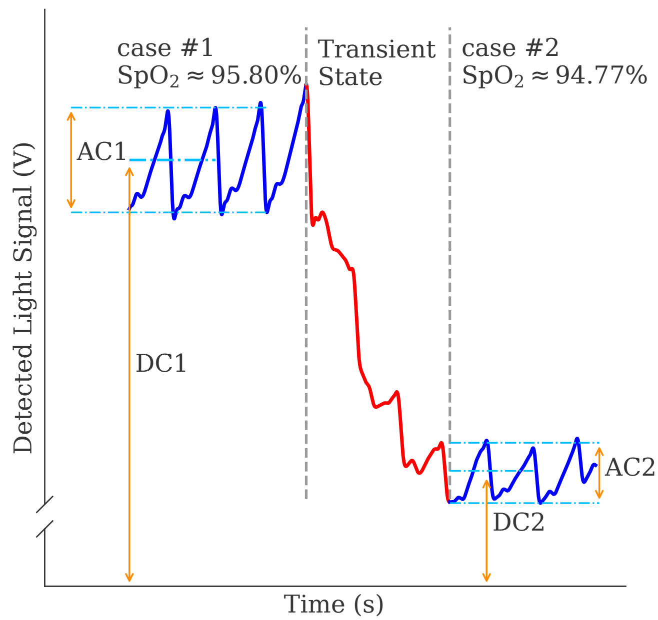
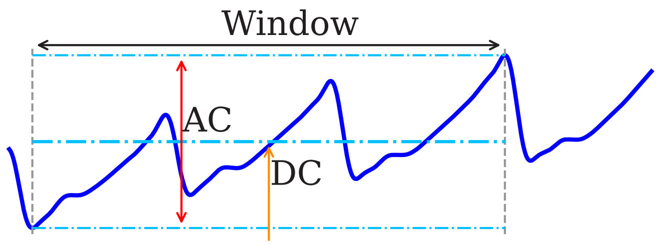


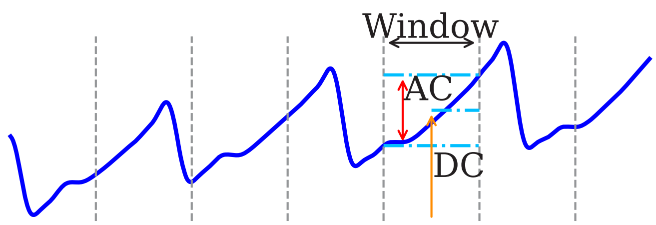
Fig. 1. AC and DC components of PPG signal with interferences.

In this work, we propose a SpO2 monitoring technique based on flexible-window filtering of PPG signals. The window width of the PPG filter is configured autonomously according to the character of real-time signals. In this way, the proposed method can adapt to changes in the PPG signals while suppressing the various interferences caused by ambient light scattering, reflections, and motion artifacts. In addition, an additional reference is not desired, minimizing the hardware cost and power consumption. In-vivo measurements with prototypes show the improvement in the precision of SpO2 monitoring in comparison to the conventional methods.

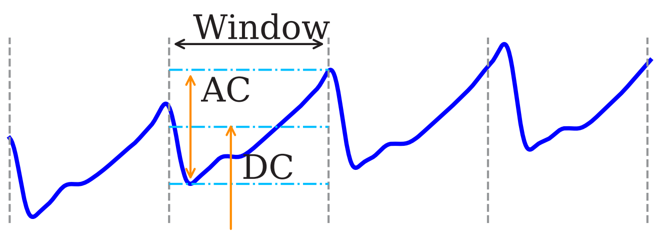
The rest of this paper is organized as follows. In section



(a) Too wide window



(b) Too short window



(c) Appropriate window

Fig. 2. PPG Filter with difference window widths.

II, the proposed SpO2 monitoring technique is described. Experimental results are presented and analyzed in section III. Finally, section IV concludes the paper.

II. PROPOSED TECHNIQUE

As shown in Fig. 1, a PPG signal appears as an AC component on a DC component. The calculation results of SpO2 in equation (1) are related to both AC and DC components of the PPG signal [12]. In an interference-free environment, the detected light signal is stable, as shown in case #1 or case #2, the accurate SpO2 value can be obtained by equation (1). If there is an interference induced by ambient light scattering, reflections, or body motion, DC level will be deviated, leading to a significant calculation error of SpO2.

Conventionally, the interferences in a PPG signal are filtered with a fixed-time window to improve the accuracy of SpO2 monitoring. As shown in Fig. 2(a), if the window is wider than expected, the change of DC component in the transient state could be mistaken as an AC signal, resulting in an error in SpO2 calculation. In addition, the over-wide window leads to a low detection rate. In comparison, a short window may cut the actual AC swing range, as shown in Fig. 2(b), also degrading the measurement accuracy of SpO2. In addition, the short window is more sensitive to high-frequency interferences. The appropriate window width is shown in Fig. 2(c), where the full scale of the PPG signal applies to the SpO2 calculation,

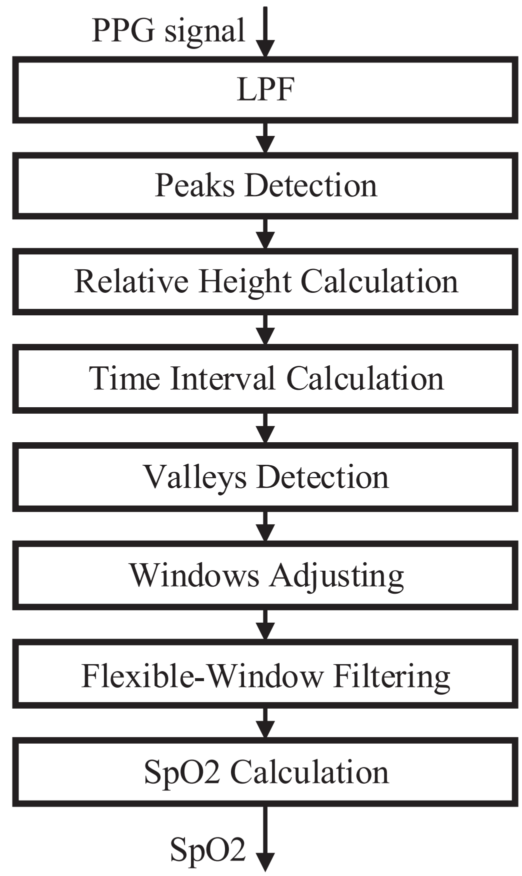


Fig. 3. Operating flow of proposed technique.

resulting in the highest precision. As a result, how to get an appropriate window in the PPG waveform remains a design difficulty in SpO2 monitoring.

To set appropriate windows real-timely on a PPG waveform, a flexible-window filtering technique is proposed for SpO2 monitoring. The key point is to select flexible boundaries for the windows based on the prominent peaks. In this way, the SpO2 calculation can avoid the impact of the DC drift, making it adaptive to various interferences. As a result, more accurate SpO2 can be achieved.

The flow of this algorithm is summarized in Fig. 3. First of all, the original PPG signal is filtered by a low-pass filter (LPF) to remove the high-frequency noise and interferences. Due to the strong correlation between AC, DC component, and peaks values of PPG signal, the peaks and valleys are set as the initial boundaries. Then, the peaks on the PPG waveform are picked out.

The real-time operation of window adjusting is described by Fig. 4. Among the peak points, we select a "2^{nd}-order peak" which is larger than its previous and subsequent points, where n of them are selected randomly to insert the boundaries of windows, as shown in the first part of Fig. 4. The height of each 2^{nd}-order peak over the adjacent valley can be calculated, which is annotated as the relative height H_i, as shown in the

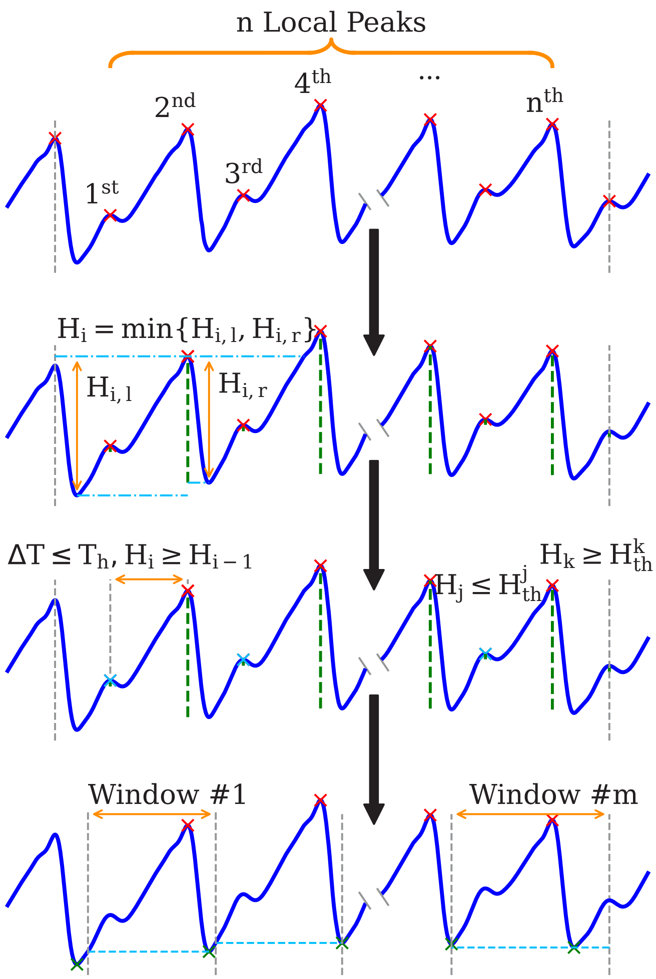


Fig. 4. Real-time operation of flexible-window filtering technique.

second part of Fig. 4. To calculate H_i of each peak, the horizon is found by searching towards the left and right sides till a higher peak appears. The relative height on the left side of each peak is annotated as $H_{i,l}$, and the right-side height is $H_{i,r}$. Then, the minimal value of $H_{i,l}$ and $H_{i,r}$ is selected as the relative height value H_i of the corresponding peak. In addition, a threshold H_{th} is introduced to regard the $H_i < H_{th}$ points as the ineffective height to further suppress the impact of interferences. In the case of a fixed window, the light absorbance will change versus the input signal induced by the variations of light intensity or skin conditions. To handle the uncertain signal range, the threshold H_{th} is updated adaptively versus the relative heights, as shown in equation (2).

$$H_{thr}^{i} = H_{thr}^{i-1} + k \times (H_i - H_{thr}^{i-1}), \qquad (2)$$

where the coefficient k is a preset damp factor to update the threshold. A higher k makes the threshold susceptible to various interferences, while a lower k may not be sufficient to handle the signal changing.

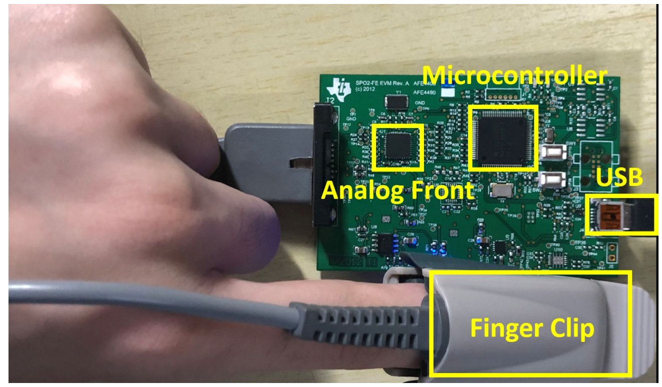


Fig. 5. Experimental setup for in-vivo testing.

An interference-induced notch may lead to multiple adjacent peaks carrying duplicated information. In the proposed technique, a time interval threshold T_h is set to deal with the issue. When two peaks are closer than T_h, the time interval will help to neglect a peak with the threshold H_{th}. In this case, the larger one between H_i and H_{i+1} is adopted. According to the carrier frequency of PPG signals, the time interval T_h is set to a value that is close to the heart rate [13] , such as 0.5 seconds. As a result, the effective peak points are selected for the subsequent calculation, as shown in the third part of Fig.4. Meanwhile, the effective valleys of the PPG waveform can also be selected as the boundaries of the windows, as shown in the fourth part of Fig. 4. The selected peak and valley are the maximal and minimal points in a window, which can be used to calculate the AC value in equation (1). Finally, the SpO2 can be obtained while the interferences can be filtered out by the flexible-window-based filtering.

III. EXPERIMENT RESULTS

The proposed technique is validated by a SpO2 monitoring prototype, as shown in Fig. 5. The finger clip sensor on the AFE4400 module collects analog PPG signals. The wavelength of red light is about 660 nm, while infrared light is about 900 nm. The analog front is used to amplify the sensing signals and digitize the analog PPG signal at a sample rate of 500 Hz, and a microcontroller (MSP430F5529) is employed to operate the whole system. The PPG data is pre-filtered by a 10 Hz low-pass filter and then processed by the proposed filtering technique.

The SpO2 monitoring technique is validated by in-vivo experiments and compared to conventional methods. The SpO2 curves obtained by proposed flexible-window filtering as well as the conventional fixed-window filtering are shown in Fig. 6. The step width of fixed-window in the conventional method is set to be close to the average value of the slots in Fig. 7 to make a comparison. The results show that the flexible-window technique achieves a SpO2 curve more smoothly than the conventional fixed-window method, indicating that the proposed method provides stronger immunity to the interferences. The

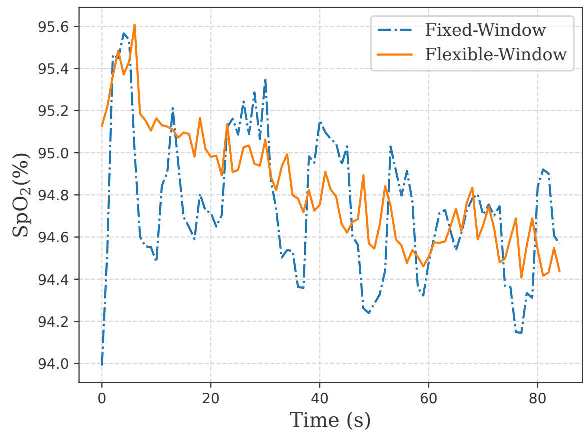


Fig. 6. Measured in-vivo SpO2 by proposed technique and conventional method.

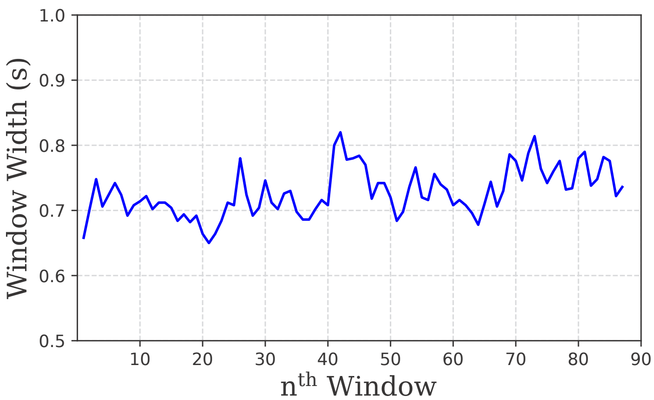


Fig. 7. Adjusting of window width in real time.

specification of Mean Absolute Percentage Error (MAPE) [14] is adopted to evaluate the accuracy of the SpO2 values:

$$MAPE = \frac{100}{N} \sum_{i=1}^{N} \left| \frac{mean - m_i}{mean} \right|, \tag{3}$$

where $mean$ is the averaged SpO2 and m_i is the measured SpO2 at different times. The comparison results are summarized in Table I, where the proposed technique shows much lower MAPE than the conventional method.

IV. CONCLUSIONS

In this work, we demonstrate a SpO2 monitoring technique based on flexible–window filtering, to get rid of various interferences on the PPG signals, such as ambient light scattering, reflections, and motion artifacts. The filtering window is self-adapted to the characters of the input PPG waveform, rejecting various frequency components of interferences. The proposed technique is validated by in-vivo testing on the human body through a prototype, which is also compared to the conventional fixed-window methods. Measured results show that the proposed technique achieves an average MAPE which is 46% higher than the conventional method, indicating a much stronger immunity to various interferences.

TABLE I
MAPE OF MEASURED SPO2

Sample	#1	#2	#3	#4	#5	#6	#7
Fixed-Window	0.721	0.287	0.323	0.403	0.388	0.554	0.415
Proposed Method	0.280	0.150	0.229	0.300	0.374	0.271	0.181
Sample	#8	#9	#10	#11	#12	#13	Mean
Fixed-Window	0.877	0.845	0.396	1.930	0.206	0.296	0.587
Proposed Method	0.446	0.356	0.211	0.867	0.104	0.235	0.308

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