NON INVASIVE VASCULAR CHARACTERIZATION BY
BLIND SYSTEM IDENTIFICATION

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ABSTRACT
In this paper, the transfer function of the upper arterial tree from heart to upper extremities is estimated via cross-relation based blind source identification. The photoplethysmogram from left and right arm index fingers were recorded at 275 Hz at 16 bits of resolution. The model order has been evaluated utilizing SVD decomposition of the ordered data matrix. After preprocessing the PPG signal, the AC signal is utilized to estimate the impulse response of the arteries from the heart to the left and right indices respectively. The proposed technique can be valuable in non-invasive vascular characterization of patients suffering from diseases affecting their arteries.

KEY WORDS
Modelling, cross relation, photoplethysmogram

1. Introduction
Cardiovascular system properties are known to be greatly affected by a person’s state of health [1]. One example of the practical tools for the non-invasive, direct vascular characterization of patients is the flow-mediated vasodilation response (FMD) [2]. This technique is known as the gold standard as it produces a reliable assessment of the endothelial function [3]. However, FMD is considered semi-traumatic as blood supply has to be stopped for up to five minutes in order to observe changes in the dilation of the arteries [3]. Furthermore, errors in the measurement of the increase in artery diameter still happen even when a well-trained technician makes the experiment as the artery walls have to be visible all the time when imaged through high-resolution ultrasound [3].

Less traumatic techniques based on non-invasive methods have been proposed, among them the two most prominent being the non-invasive measurement of the blood pressure via a Finapres device [4] and photoplethysmogram (PPG) based systems [5-6]. In [5], the pulse-transit time is exploited, while others [6] have actively investigated time domain features such as the second derivative of the PPG. In order to mitigate the effect of intersubject variability, a differential approach has also been proposed using parametric modelling [7]. Whatever technique is devised, the ultimate aim is a totally non-invasive scheme to help the physician towards a better diagnostic. This highlights the role of optical methods which have found a special place as besides being non-invasive, they do not require galvanic contact making them intrinsically safe, further widening their scope of application.

In this paper, a blind system identification (BSI) scheme is implemented to characterize the transfer functions from the heart to two different anatomical points in the human body (right and left index fingers) using the PPG. Among various BSI techniques, the cross relation technique [8] has been adopted. This choice is based on the fact that high SNR PPG signals, where cross relation works best, can be easily obtained. In [9] a similar method is proposed where the channel transfer function can be estimated in real-time, adapting it to the patient’s condition. Our approach is different in the sense that we only consider moving average difference equations (all-zeros FIR) and totally non-invasive PPG signals from a real human subject. The choice of a zeros-only system is based on the practical limitation in obtaining more than two simultaneous PPG leads in our instrumentation.

2. Theoretical Background

The basic model in the case of blind system identification via cross-relation is shown in figure 1. Full details of the derivation can be found in [8] and only a simplified version is presented here. In this model, a single source $s$ excites two FIR systems characterized by their transfer functions $H_1(z)$ and $H_2(z)$ with respective impulse responses $h_1[n]$ and $h_2[n]$. $x_1[n]$ and $x_2[n]$ are the outputs of $H_1$ and $H_2$ respectively, therefore the following equations can be written:

$$x_1 = h_1 \otimes s$$
$$x_2 = h_2 \otimes s$$

Where the symbol $\otimes$ represents time domain convolution.
Convoluting the output from one channel with the impulse response of the other channel leads to:

\[ x_1 \otimes h_2 = h_1 \otimes s \otimes h_2 = h_1 \otimes x_2 \]  (3)

which can be rearranged as:

\[ x_1 \otimes h_2 - x_2 \otimes h_1 = 0 \]  (4)

In this paper, we assume that both \( h_1 \) and \( h_2 \) channels have the same order (L-1) and N sample points are available from each channel. This assumption is based on the fact that the anatomical paths from the heart (source of signal excitation) to the upper extremities (PPG recording sites) are not very dissimilar.

Equ. (4) can be written in matrix form:

\[
\begin{bmatrix}
X_1 \\
X_2
\end{bmatrix}
\begin{bmatrix}
h_2 \\
h_1
\end{bmatrix} = 0
\]  (5)

The ordered data matrix \( X_j \) for \( j = \{1,2\} \) are given by:

\[
X_j = \begin{bmatrix}
x_j(L-1) & x_j(L-2) & \ldots & x_j(0) \\
x_j(L) & x_j(L-1) & \ldots & x_j(1) \\
\vdots & \vdots & \ddots & \vdots \\
x_j(N-1) & x_j(N-2) & \ldots & x_j(N-L)
\end{bmatrix}
\]  (6)

and have dimensions of \((N-L+1) \times (L)\). \( x_j(0), \ldots, x_j(N-1) \) are the N data samples recorded from channel \( j \).

\([h_2 \ h_1]^T\) is a \((2L) \times (1)\) column vector:

\[
h_j = \begin{bmatrix}
h_j(0) \\
h_j(1) \\
\vdots \\
h_j(L-1)
\end{bmatrix}
\]  (7)

Equ. (4) leads to a system of \((N-L+1)\) equations and \(2L\) variables. The necessary condition for this system to have a solution is:

\[ N \geq 3L-1 \]  (8)

In other words, we must have enough samples to be able to identify the two channels, which is fortunately usually the case. When \( N = 3L-1 \), \([X_1 \mid -X_2]\) becomes square and obviously to find a solution other than \([h_2 \ h_1]^T = 0\), it must not be full rank. In the latter case, any of the variables \( h_j(k) (j = \{1,2\} \text{ and } k = \{0,\ldots, L-1\}) \) is fixed arbitrarily to one (for. ex.) and the rest of the equations are solved. In other words, the solution to the BSI will be valid up to a constant. This could have also been shown much earlier by introducing a constant \( \alpha \neq 0 \) and rewriting Equ. (4):

\[ x_1 \otimes (\alpha \times h_2) - x_2 \otimes (\alpha \times h_1) = 0 \]  (9)

Clearly, Equ. (4) and (9) are equivalent for any \( \alpha \neq 0 \).

As the number of data samples \( N \) is generally much larger than \((3L-1)\), the system of linear equations in (5) becomes over-determined and can be solved by a least square approach [8]. Commercially available software’s such as MATLAB (The Mathworks, Inc.) offer built-in functions for the least-square solution of multiple linear equations.

It should be noted that the cross-relation technique assumes that the order of the channels are known in advance. In practice, this condition can be difficult to establish or verify via conventional measures (e.g. RMSE, Akaike information criterion (AIC) or final prediction error (FPE)) as these criterions are not applicable for the simple reason that neither the input signal nor the channel impulse response are not available (see figure 1). Another condition is that there should be no common dynamics (shared zeros as we consider FIR systems only). In [8], this condition is elaborated under identifiability conditions. In [8] and [10], similar procedures are proposed based on the singular value decomposition (SVD) of \([X_1 \mid -X_2]\). In this method, the order is first overestimated and then SVD is effected on \([X_1 \mid -X_2]\). If \( K+1 \) singular values are indeed very small, based on the knowledge of noise level, the true number of the order is the initial (overestimated) order minus \( K \). A similar method for order determination is utilized in this work.

3. Methods

3.1 Data acquisition set-up

A pair of PPG signals was acquired through the serial ports of two pulse-oximeter evaluation modules (OEM-601 from DolphinMedical, Inc.). The sampling rate was increased to 275 Hz by the manufacturer of the modules upon our request. Left and right index fingers were used for probe placement. Sensor signals were internally digitized by the modules at a fixed resolution of 16 bits. Each module was connected to a laptop running a proprietary software provided by the manufacturer. The length of each recording was approximately 90 seconds. All data were saved under a condensed format by the proprietary software and subsequently exported to an ASCII file for further analysis.

PPG signals were acquired from a healthy male volunteer (age 32 years). The subject was asked to refrain from
eating, smoking or drinking tea/coffee for at least 3 hours before the experiment and rested 10 minutes in the laboratory before the start of the data acquisition. The supine position was used on a soft mattress with arms and legs remaining at the heart level during the length of the experiment.

3.2 Pre-processing

PPG signals are composed of two components: a pulsatile (known as the AC) and a slow-varying DC. The DC part is more related to the respiration and slow changes in the diameter of the arteries rather than the effect of heart pulsations. The AC contains the dynamic information which can characterize the transfer function and has been investigated. Thus, before proceeding to the BSI algorithm, the AC and DC components have been separated so that only the AC part is considered. The following pre-processing was effected on each record of raw data:

i. Trend-removal
ii. Band-pass filtering (from 0.1 Hz to 15 Hz).
iii. Delay compensation.
As data acquisition is manually started, there is no guarantee about both channels being synchronously sampled. Therefore an arbitrary delay exists between the two channels. Both traces are aligned in time by this part of the pre-processing.
iv. Resampling at 55 Hz.
v. Segmentation (300 samples).
vi. Segment trend removal.

4. Results

4.1 PPG sample records

PPG sample signals after pre-processing are shown in figure 2.

4.2 Order determination

The procedure indicated in [10] was followed whereas the singular values of \([X_1 | -X_2]\) were evaluated by standard SVD. Initially, the overestimated order was set to 19 (L=20) with a segment length N = 300 samples.

The contribution of each of the singular values is plotted in figure 3. It can be seen that after the 10th singular value, the amount of relative energy becomes negligible (<1%). For quantification purposes, table 1 shows the relative value of each singular value (left column) and the cumulative contribution (right column) for the first 12 singular values of \([X_1 | -X_2]\).

Table 1: Relative and cumulative contribution of each singular value obtained from SVD decomposition of \([X_1 | -X_2]\) (same data as fig. 3).

<table>
<thead>
<tr>
<th>Singular value order</th>
<th>Relative % of total</th>
<th>Cumulative %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>28.5</td>
<td>28.5</td>
</tr>
<tr>
<td>2</td>
<td>26.6</td>
<td>55.1</td>
</tr>
<tr>
<td>3</td>
<td>13.7</td>
<td>68.9</td>
</tr>
<tr>
<td>4</td>
<td>10.4</td>
<td>79.3</td>
</tr>
<tr>
<td>5</td>
<td>5.4</td>
<td>84.8</td>
</tr>
<tr>
<td>6</td>
<td>4.0</td>
<td>88.8</td>
</tr>
<tr>
<td>7</td>
<td>2.4</td>
<td>91.3</td>
</tr>
<tr>
<td>8</td>
<td>1.9</td>
<td>93.3</td>
</tr>
<tr>
<td>9</td>
<td>1.4</td>
<td>94.8</td>
</tr>
<tr>
<td>10</td>
<td>1.0</td>
<td>95.8</td>
</tr>
<tr>
<td>11</td>
<td>0.8</td>
<td>96.7</td>
</tr>
<tr>
<td>12</td>
<td>0.7</td>
<td>97.4</td>
</tr>
</tbody>
</table>

Table 1 shows that by neglecting the singular values which contribute relatively less than 0.7%, over 97% of the total signal energy is retained. In other words, the 12 first singular values (i.e. limiting L to 6) conserve >97%
of the total energy in the signal. Therefore the order (L-1) will be fixed at 5 in the rest of this work.

4.2 Impulse response determination

For the signal pair in figure 1, the cross-relation BSI has been implemented by solving the over-determined system of linear equation (5). Figure 4 shows the results of the determination of the impulse response for \( h_1 \) and \( h_2 \).

![Figure 4: Estimated impulse responses for channels 1 and 2 from the pair of signals in figure 2.](image)

5. Conclusion

A non-invasive BSI technique based on processing of PPG signals has been developed. PPG signals are one of the most convenient signals to record, as the sensor is optical, with a high SNR. The proposed technique exploits the information contained in the contour of the PPG signal, which conveys useful information about the state of the arteries, making it well suited for vascular evaluation in diseases such as diabetes or atherosclerosis. Compared well-accepted flow-mediated vasodilation, the proposed technique is far less traumatic. With more PPG sensors types, other anatomical sites such as the chest or the forehead become also accessible. Increasing the number of recording sites to more than two will also allow for a pole-zero (IIR) system to be considered. Current work based on Windkessel models is under investigation to apply the proposed technique to PPG obtained from patients suffering from diabetes. In this framework, the impulse responses from diabetic subjects will be compared to healthy ones.

6. Acknowledgements

This work was supported by an Intensive Research Priority Areas grant (IRPA-02-02-0106-EA258) from the Ministry of Science, Technology and the Environment, Malaysia.

References: