Temporal Alignment of Asynchronously Sampled Biomedical Signals

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Abstract

Temporal alignment of signals obtained using different acquisition systems is often complicated by asynchronous sampling. In the current study we aligned 3-lead ECGs recorded in a phonocardiogram setup with 12-lead Holter ECGs.
Two signals with common morphology (lead II from both devices, recorded synchronously with closely placed electrodes) were resampled to similar sample rates. An initial alignment was obtained by cross-correlation analysis. Next, instantaneous delays were estimated using cross-correlation analysis of the two signals in a running window of four seconds duration. The first derivative of the instantaneous delays is related to the variation in sample rate between signals. Consequently, a smoothed version of this derivative was used for local resampling of one of the signals before final alignment.
Visual inspection confirmed that all recordings were synchronized by the alignment procedure. The mean and standard deviation of the delay between R-peaks in the synchronized ECGs were 0.3±4.5 ms.
We present a fully automated method for alignment of signals sampled asynchronously with drifting clocks.

1. Introduction

In multimodality studies where signals from different modalities, like ECG and image modalities are used in combination, temporal synchronisation is often important. However, it is often not possible to sample signals from all modalities with the same acquisition systems. The result is often asynchronously sampled signals. One method to synchronize multi-modality signals is to record the same signal with each acquisition system. Temporal alignment of these signals is often complicated, not only due to out of sync timestamps and different sample rates, but also due to an often overlooked problem of drifting clocks, which results in varying delays between signals. Drifting clocks are especially critical in long recording sequences.

Alignment of asynchronously sampled time series is a challenge in many research fields from distributed microphone arrays [1] to geospatial animal tracking sensors [2]. Generally, the problem is a registration problem, and in case of instable sample rates the problem is a warping problem where the relationship between the time axes are non-linear.

The current study was initiated by a practical alignment problem. We had recorded long sequences of phonocardiography and seismocardiography from pacemaker patients [3]. The acquisition system recorded only 3-lead ECG and since we needed 12-lead ECG, a 12-lead ECG was recorded simultaneously byHolter. When we attempted to align the lead II signals from the two devices we found that linear alignment was insufficient due to drifting or suddenly changing sample rates, see figure 1.

In the current study we describe a method for alignment of asynchronously sampled biomedical signals using a correlation based time warping method, inspired by Nielsen et al [4]. Compared to traditional time warping methods the focus of the current method is gentle warping which preserves signal morphology.

2. Methods

The current method included 3 main steps. First the signals were aligned using a coarse alignment, next the running delay between the signals was estimated using cross-correlation in short segments and finally one of the signals was resampled. We define one signal as the reference signal $\boldsymbol{r}$ and the other signal as the query signal $\boldsymbol{q}$.

2.1. Dataset

For the current study we used 15 ECG recordings from the previously mentioned pacemaker study [3]. The 3-lead ECG was recorded using an iWorx S228 acquisition system (iWorx, Dover, US) with a sample rate of 5000 Hz. 12-lead ECGs where recorded using General Healthcare's SEER Holter recorder (GE Healthcare, Milwaukee, WI, USA) with a sample rate of 500 Hz. Durations of the

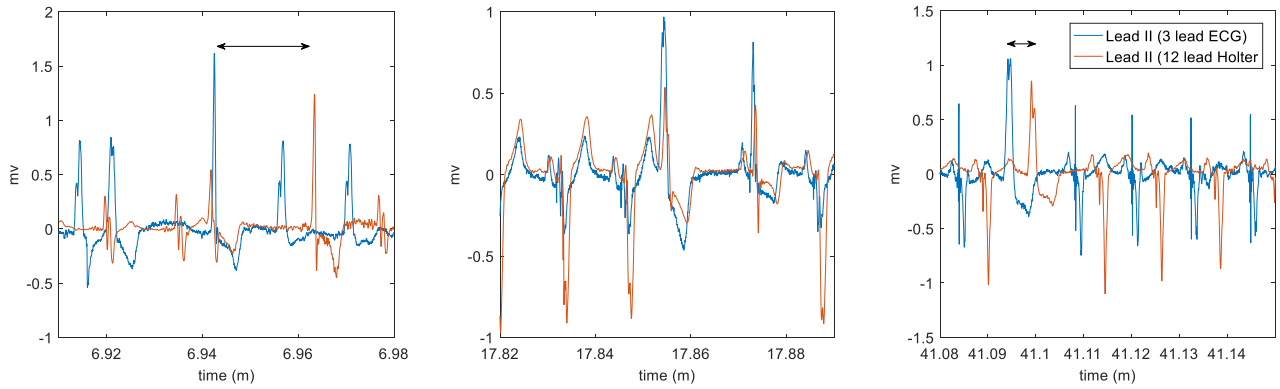

Figure 1. Zoom at three different time points after initial course alignment by cross-correlation. The 3-lead ECG is ahead of the 12-lead Holter in the beginning and end of the recording, while the two signals are well aligned in the middle of the recording after about 18 minutes. Further alignment is needed.

recordings where approximately 45 minutes. Lead II signals from both devices, recorded with closely placed electrodes, were used for alignment.

2.2. Pre-prossesing

Initially both ECG signals were band-pass filtered (2.5-150 Hz) using an 8. order Butterworth filter and 50 Hz electric hum was reduced using a notch filter. The 3-lead ECG signal was then down sampled to 500 Hz.

2.3. Initial alignment

In the current case, one acquisition system might be turned on and acquisition started before the other system. In such cases, the delay between the onsets of the signals might be very large. Therefore an initial alignment was obtained using cross-correlation analysis. Delays were estimated between sub-segments (240 seconds long) of the query signal with the full length of the reference signal. The median delay was then used for a coarse alignment of the two signals.

2.4. Stepwise delay estimation

Next, the signals $\boldsymbol{r}$ and $\boldsymbol{q}$ were dived into parallel sub-segments $\boldsymbol{r_i}$ and $\boldsymbol{q_i}$ where i corresponds to the segment number. The length of the segments is denoted L. Next, delays between the $\boldsymbol{r_i}$ and $\boldsymbol{q_i}$ segments were estimated using a unbiased and normalized cross-correlation analysis. The correlations were arranged in a matrix $\boldsymbol{R_{rq}}$ where columns were segment-wise cross-correlations between the two signals.

$$\boldsymbol{R_{rq}}(k,i) = \frac{L}{L-|k|}\frac{\sum_{m=1}^{L}\boldsymbol{r_i}(m)\boldsymbol{q_i}(m-k)}{\sqrt{\sigma_{r_i}^2+\sigma_{s_i}^2}}$$

k was the lag of the cross-correlation ranging from –L/2 to L/2. The segment length (L) has to be long enough to capture the morphology of the signal while it has to be short enough not to be distorted significantly by changes in sample rate. In the current application the window length was chosen to be 8 seconds.

If the delay between the signals is constant the maximum points in the cross-correlations will form a horizontal line in the $\boldsymbol{R_{rs}}$ matrix, while in cases of differing sample rates the maximum peaks will deviate from the horizontal line, see figure 2.

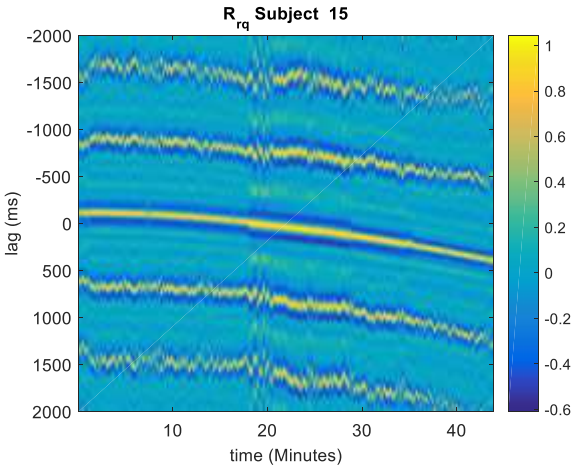

Figure 2. Plot of the $\boldsymbol{R_{rq}}$ matrix which holds the segment-wise cross-correlations of the two signals. The maximum peaks of the cross-correlations form a distinct line starting at approximately lag -100 ms and ending at lag +400 ms. The delay between the two signals is not constant, nor linear.

The optimal alignment between the two signals will be the alignment that maximizes the correlation between the signals in each segment. Therefor a dynamic programming

scheme was applied to trace a route that goes though all colons in $\boldsymbol{R_{rs}}$ and maximizes the sum of correlations ($\boldsymbol{S}$). To find the optimal route, the accumulated optimum correlation was calculated iteratively for each point in $\boldsymbol{R_{rq}}$. The accumulated correlation for the first segment equals the first colon in $\boldsymbol{R_{rq}}$.

$$\boldsymbol{S(k,1)} = \boldsymbol{R_{rq}}(k,1)$$

In the remaining columns the optimal sum of correlations was estimated as $\boldsymbol{R_{rq}}(k,i)$ added to the local maximum in the previous column of $\boldsymbol{S}$.

$$\boldsymbol{S(k,i)} = \boldsymbol{R_{rq}}(k,i) + \max(\boldsymbol{S}(k+\boldsymbol{j}), i-1)$$
$$\boldsymbol{j} = -t, -t+1, \ldots\ldots t$$

$\boldsymbol{j}$ is an index vector which covers the points closest to $\boldsymbol{S}(k,i)$ in the previous column of $\boldsymbol{S}$. $\boldsymbol{j}$ is bounded by t which is the slack, meaning the maximum delay variation between two segments. The slack was chosen to 8 samples corresponding to a maximum sample rate deviation of 1 one sample per second.

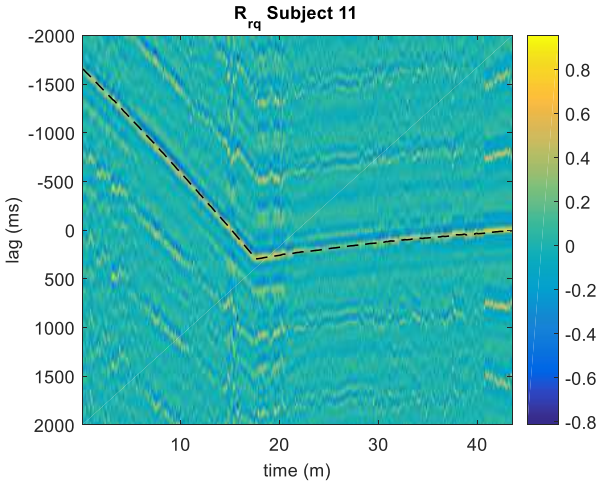

Figure 3. A second example of the segment-wise cross-correlations matrix $\boldsymbol{R_{rq}}$ and the traced line (dashed line) of delays $\boldsymbol{d}(i)$. The sample rate of one of the systems changes suddenly after 18 minutes of recording.

For each point in $\boldsymbol{S}$ the index of the point in $\boldsymbol{S}(k,i-1)$ which maximized $\boldsymbol{S(k,i)}$ is saved for backtracking. After estimation of $\boldsymbol{S}$, backtracking stating in the maxima in the last column was used to identify the route $\boldsymbol{d}(i)$ which maximize the correlation. Thereby $\boldsymbol{d}(i)$ describes the optimum lag between the two signals at segment i. An example on maximum correlation route can be seen in figure 3.

2.5. Resampling

The segment delays were used for resampling of the query signal using the following scheme, figure 4:

1. The segment delay vector $\boldsymbol{d}$ was up-sampled to $\boldsymbol{dn}$ which covers the full length of the signal using interpolation, see figure 4 b. $\boldsymbol{dn}$ is then the delay at sample level.
2. $\boldsymbol{dn}$ is converted to an integer vector $d\mathbb{Z}$.
3. The derivative of $d\mathbb{Z}$ was calculated to give $\Delta d\mathbb{Z}$, see figure 4 d.
4. A positive value of $\Delta d\mathbb{Z}$ means adding a sample to the query signal and a negative number means removing a sample from the query signal.

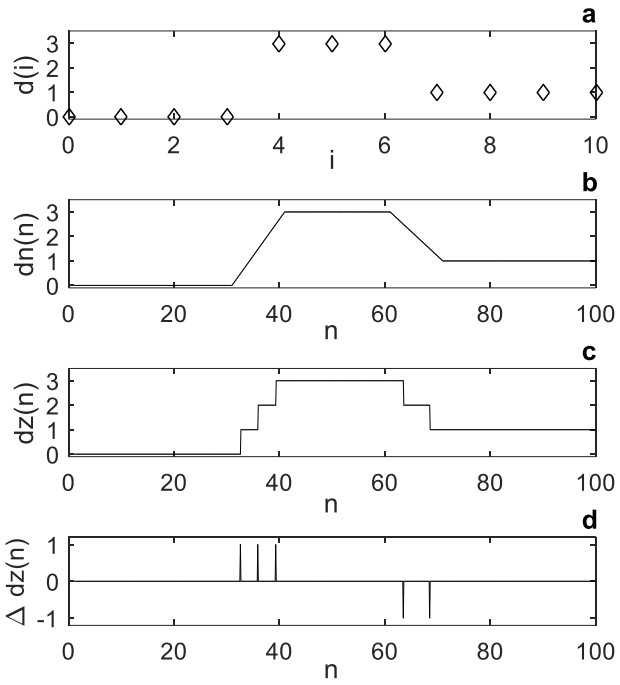

Figure 4. Plot demonstrating the resampling scheme. a: Segment delays. b: Delays at sample levels. c: Discrete delays. d: Derivative curve where a positive peak indicates removal of a sample from the query signal and a negative peak means adding a sample.

2.6. Validation

We validated the current method by visual inspection of the alignment between the lead II from the 3-lead ECG's and the 12-lead ECG's. In addition, the delay between R-peaks in the two signals was measured in windows of 10 seconds in the beginning, middle and end of each recording.

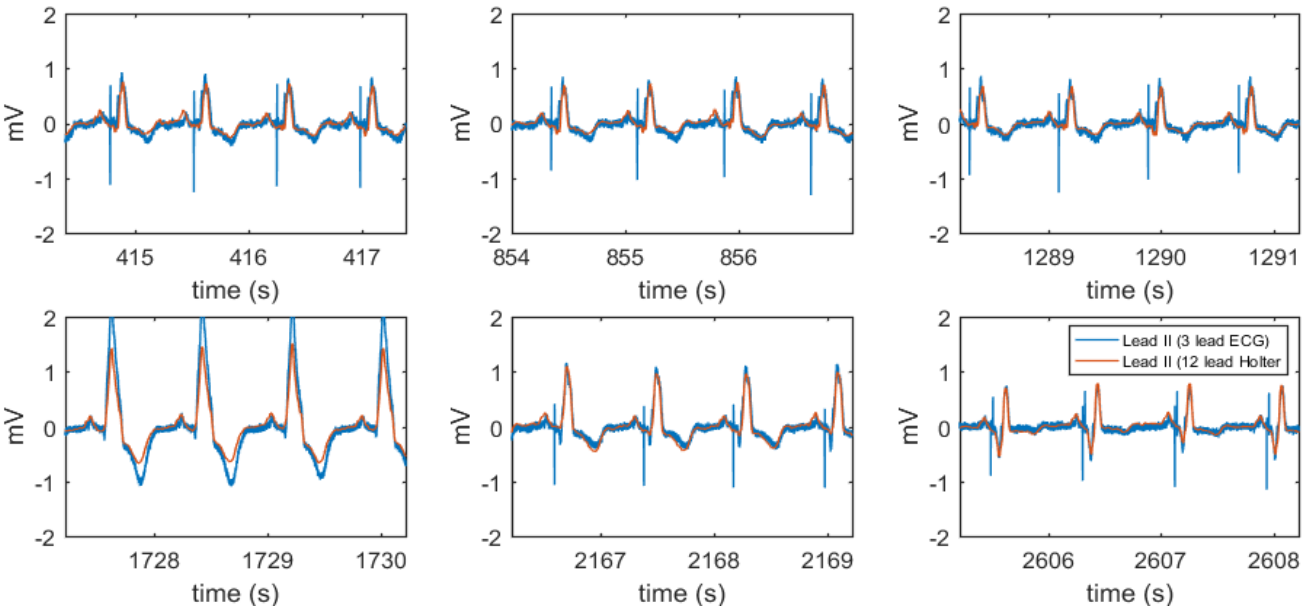

Figure 5. Plot demonstrating the final alignment between the two signals at six different time points.

3. Results

Visual inspection confirmed that all 15 recordings were synchronized by the alignment procedure. An example is shown in figure 5. The mean and standard deviation of the delay between R-peaks in the synchronized ECGs was 0.3 ±4.5 ms.

4. Discussion

The current study was initialized by a practical alignment problem in a cardiovascular research study. Correct alignment of asynchronously sampled time signals is essential before further analyses of multimodality data. We present a fully automated method for alignment of signals sampled asynchronously with drifting sample rates. The method has estimation of segment correlations in common with traditional correlation based time warping methods [4]. However where other methods warp the signal in each segment, the current method uses the segments to estimate a running delay, which is then used for resampling of the full query signal. Thereby the warping is done in wider time frame and the shape of the signal is preserved.

The method was used for alignment of a 3-lead and 12-lead ECG. The results showed robust alignment between the two signals. The bias of alignment was negligible as the average error was 0.3 ms and standard deviation of the error was 4.5 ms which is less than the typical time error of common R-peak detection algorithms [5]. Thereby asynchronously sampled time signals can be aligned appropriately for use in further research.

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