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Optimization of heartbeat detection based on clustering and multimethod approach

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Abstract— **In this paper, an approach for optimizing heartbeat locations as detected in time by multimethod approach is proposed. The approach builds a two-dimensional representation of heartbeat locations obtained by several independent detection methods. The representation depends on heartbeat time instants and beat-to-beat intervals. It is first transformed into a smoothed two-dimensional histogram of points indicating individual heartbeat detections. Heartbeat time instants are determined as local maxima in the histogram. We tested our approach on signals acquired by optical interferometer. Seven subjects participated in the experiment, beginning by an ergometer exercise until they reached submaximal heart rate. A resting period followed, during which optical interferometric signal was taken unobtrusively in parallel with referential ECG. The proposed detection procedure was capable of tracking the changing heart rhythm by analyzing optical interferometric signals and comparing the results to the referential ECG recordings. Sensitivity 97.13±2.00% and precision 97.82±2.09% were obtained. Mean absolute error between detected beat-to-beat and referential RR intervals yielded 20.05±8.38 ms and corresponding mean relative error 7.47±3.19%.**

I. Introduction

Unobtrusive monitoring of heartbeat has become quite a popular field of research lately. Many different approaches for such monitoring have been developed by combining different types of sensors that detect electrical, audible or mechanical activity of the heart even when there is no direct contact of the sensor and a person's body, using special signal processing methods – a short survey is given in [3]. Also a possibility of monitoring the heartbeat by using optical sensors [1, 2] has been investigated; these can be used as bed sensor [3, 4, 6] or even body sensor [5].

The main problem of methodologies for detecting heartbeats is accuracy, which can be a real challenge in more demanding circumstances, including variable heart rate. One of the possible options to increase accuracy in such circumstances is to use multimodal approach and, then, to fuse several detections of heartbeats, obtained by the different heartbeat detection methods. Feasibility of this kind of heartbeat detection principle is revealed in [7].

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In this paper, we introduce a new approach, which was, in the first place, built to increase accuracy of detected heartbeats by using optical interferometer. It is based on two parameters – time instants of heartbeats estimated by multiple methods and on beat-to-beat intervals, which directly carry information on heart rate variability. A smoothed two-dimensional histogram of points is used in time versus beat-to-beat intervals.

The paper begins with a description of the methodology in Section II. The experimental protocol and results are presented in Section III. Discussion follows in Section IV, while Section V concludes the paper.

II. Methodology

Let us assume that K vectors with potential time instants of detected heartbeats $t_{i,k}^{d}$ were obtained by applying K different methods to optical interferometric signal. Each individual method detects heartbeats with a certain delay after the R waves in referential ECG signal. We allow the mean values of the delays are different for each individual method (a method bias), but their dispersion should be minimal. In order to align the detections of all methods, their bias is removed from all time instants of detected heartbeats $t_{i,k}^{d}$:

$$t_{i,k}^{a} = t_{i,k}^{d} - \overline{\tau}_k + \min\{\overline{\tau}_k\} \qquad (1)$$

where $\overline{\tau}_k$ are mean reference-to-detected delays for all K methods, estimated in advance for each k-th method. We can expect that time instants as detected by all K methods should group at each individual heartbeat. In order to use the advantage of a multimethod approach in the case of variable heart rate, we introduce additional parameter, directly related to heart rate variability. For each of the potential heartbeat time instants, we arrange beat-to-beat distances, i.e. intervals between detections of consecutive heartbeats. Thus, we construct the following scatter plot S:

$$\left\{S(x,y); x = t_{i,k}^{a} \wedge y = t_{i+1,k}^{a} - t_{i,k}^{a} \wedge k \in 1,2,\ldots,K\right\}. \qquad (2)$$

All heartbeats are now represented as points in 2D plane. Assumingly, clusters of points appear centered at each heartbeat time instant, with y coordinates in clusters equal to instantaneous beat-to-beat intervals (Fig. 1.a). The proposed approach is based on the fact that there is a high probability for points from efficient heartbeat detection methods to group into mentioned clusters, while false detections appear with a high probability as outliers. Thus, obtained clusters indicate heartbeat positions in time. These are determined by observing density of the clustered points.

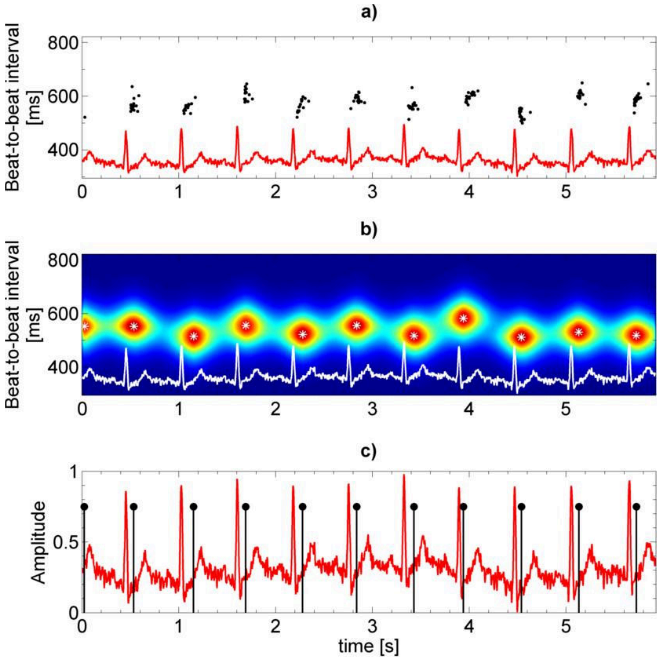

Figure 1. Steps in the optimization of the detected heartbeat positions by using the proposed approach illustrated on a 6 s long example of interferometric signal accompanied by referential ECG signal: (a) scatter plot of points from different independent heartbeat detection methods and their beat-to-beat intervals based on the analysis of interferometric signlas; (b) smoothed two-dimensional histogram with detected local maxima (white points); (c) detected heartbeats obtained as projection of local maxima from (b) onto the time axis.

Histograms mean common approach while observing densities. In our case, we are dealing with two-dimensional domain (time instants on *x* axis versus beat-to-beat intervals on *y* axis), therefore we compute two-dimensional histogram *H*. The whole plane is divided into rectangles and the number of points is counted for each rectangle. The resolution of such a grid is regulated by two parameters, namely, the number of *x*-axis bins, N_x , and the number of *y*-axis bins, N_y . Those two parameters should be selected prudently in order to prevent fusion of clusters belonging to different heartbeats if parameters are set too wide, and more isolated clusters for one heartbeat as a consequence of unsuccessful fusion if the width of bins is too narrow.

While calculating two-dimensional histogram *H*, only rough estimation of densities is obtained. In order to simplify the heartbeat detection process, smoothing of *H* is performed. We experimented with smoothing approach based on penalized least squares, which is described in detail in [8] and [9]. The degree of smoothness is varied by parameter λ. Larger values of λ lead to smoother results and vice versa. Again, parameter λ has to be set optimally in order to prevent appearance of unwanted fusion of consecutive heartbeat clusters or unsuccessful fusion of individual heartbeat clusters.

The smoothed two-dimensional histogram *S* facilitates the extraction of heartbeat time instants. Prominent local maxima in *S* represent fused heartbeat clusters (Fig. 1.b). Thus, local maxima positions t_{ij} are calculated from *S*:

$$\left\{ t_{ij} \left| \frac{\partial S\left(t_{ij}\right)}{\partial t_i} = 0 \wedge \frac{\partial S\left(t_{ij}\right)}{\partial t_j} = 0 \wedge S\left(t_{ij}\right) > p \right. \right\} \tag{3}$$

where *p* is a threshold which suppresses outliers in *S*. Finally, while projecting local maxima positions t_{ij} onto the time axis, time instants t_i of the detected heartbeats are obtained (Fig. 1.c).

III. Evaluation of results

Efficiency and accuracy of the proposed fusion approach were examined on optical signals obtained in the following experimental protocol. Seven healthy subjects, 5 males and 2 females with average age of 29.85±9.11 years, average height of 174.71±5.85 cm, and average weight of 71.85±7.86 kg, participated in experiments that were performed on a bed with inserted optical fibre. In order to acquire referential ECG signal, four electrodes were firmly attached to subject's extremities. Lead II was taken as the referential ECG signal. Observed persons were asked to cycle an ergometer until their submaximal heart rate was achieved. After that, they immediately lied back down on the mattress. The acquisition of interferometric and referential ECG signals began simultaneously and was synchronized by hardware. Signals were sampled at sampling frequency 500 Hz. Subjects were asked to lie still and in the meantime, signals were acquired for 5 minutes. With such a protocol, we obtain gradual changes of heart rate, which exposes the detection methods to an aggravated situation.

After signal acquisition, we ran 20 different heartbeat detection methods, either based on different frequency bands of interferometric signals, in relationship with mechanical or audible heart activity, or different preprocessing steps (e.g. envelope calculation), or different heartbeat detection approaches (e.g. smoothing, shape analysis, etc.). This way, we obtained 20 vectors with potential time instants of detected heartbeats $t_{i,k}^d$ for each subject. These entered a fusion process, as proposed in Section III, in order to determine final heartbeat locations in time. Time axis, *x*, was divided into $N_x = 5000$ bins for 5 minute long signal (each bin's width is 33.3 ms), while beat-to-beat interval axis, *y*, was divided into $N_y = 100$ bins covering beat-to-beat intervals from 400 to 800 ms (each bin's width is 4 ms).

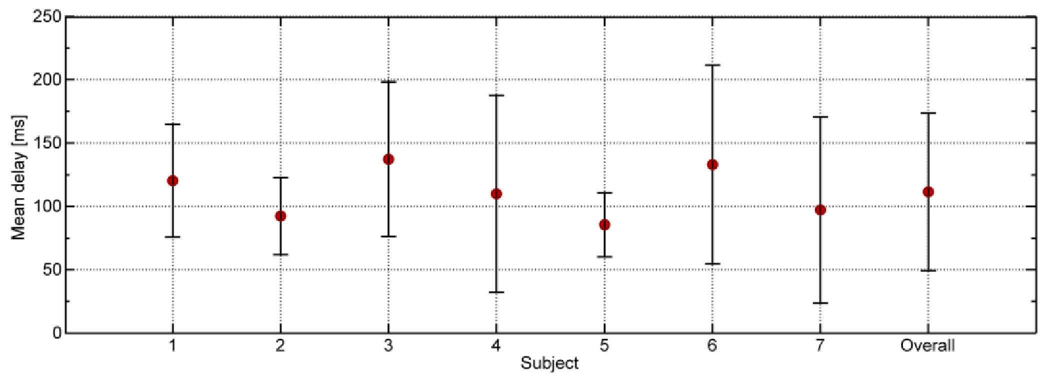

Figure 2. Mean and standard deviation of delays between reference and detected heartbeat instats for 7 tested subjects.

We experimented with smoothing parameter $\lambda = 3$, which appeared to be optimal. Threshold p is set as strict as possible, i.e. to 75% of the value of highest local maximum of the smoothed two-dimensional histogram S.

The fusion process was performed for all subjects. Finally, efficiency and accuracy of proposed approach were determined by comparing obtained heartbeat time instants with corresponding R waves from the referential ECG signal. The R wave detection was performed by Pan-Tompkins algorithm [10].

Interferometric detection efficiency is determined according to each referential R wave. Due to delays of mechanical or audible activity of the heart in comparison with the ECG signal, the detected heartbeats fall into an interval between two consecutive referential R waves. In the ideal case, exactly one detected heartbeat appears in every RR interval. Accordingly, all detected heartbeats are grouped in 3 classes:

- true positive (*TP*) – the number of first detected heartbeats in intervals between two consecutive R waves (if they exist),
- false positive (*FP*) – the number of all (false) detected heartbeats in intervals between two consecutive R waves, after the first one in the interval, and
- false negative (*FN*) – the number of all undetected heartbeats in intervals between two consecutive R waves.

With these classes, the following two efficiency metrics are introduced:

- sensitivity: $\dfrac{TP}{TP+FN}$
- precision: $\dfrac{TP}{TP+FP}$

The results for all 7 persons and overall efficiency using the proposed efficiency metrics are shown in Table I.

TABLE I. EFFICIENCY METRICS FOR THE PROPOSED METHOD OBTAINED FROM THE EXPERIMENT WITH 7 SUBJECTS.

ID	No. of ref. beats	No. of detetcted beats [TP]	No. of false detected [FP]	No. of undet. [FN]	Sensitivity [%]	Precision [%]
1	576	567	7	9	98.44	98.78
2	516	512	1	4	99.22	99.81
3	608	591	2	17	97.20	99.66
4	557	528	24	29	94.79	95.65
5	499	496	2	3	99.40	99.60
6	532	503	21	29	94.55	95.99
7	538	518	26	20	96.28	95.22
Overall	**546.57± 37.04**	**530.71± 35.22**	**11.86± 11.31**	**15.86± 10.93**	**97.13± 2.00**	**97.82± 2.09**

Accuracy of the proposed procedure was examined by using several parameters. Stable reference-to-detected heartbeat delay is most important when the regularity of heart rate is estimated. Accurate methods are expected to generate stable delays. Stability of the reference-to-detected heartbeat delays can be assessed by their standard deviation. We depict the established delays in Fig. 2. Overall reference-to-detected delay yields 110.76±55.76 ms.

Comparing time distances between consecutive detected heartbeats to corresponding referential RR intervals can deepen insights into detection accuracy. Mean absolute and relative errors for all 7 subjects were computed. Results are shown in Fig. 3. Overall mean absolute error was 20.05±8.38 ms, while overall mean relative error was 7.47±3.19%.

IV. DISCUSSION

Results presented in Table I confirm high efficiency of the proposed approach. Obtained sensitivity and precision are comparable to the existing methods [3,4,5,6], even in the case of optical signals acquired in disturbing environment.

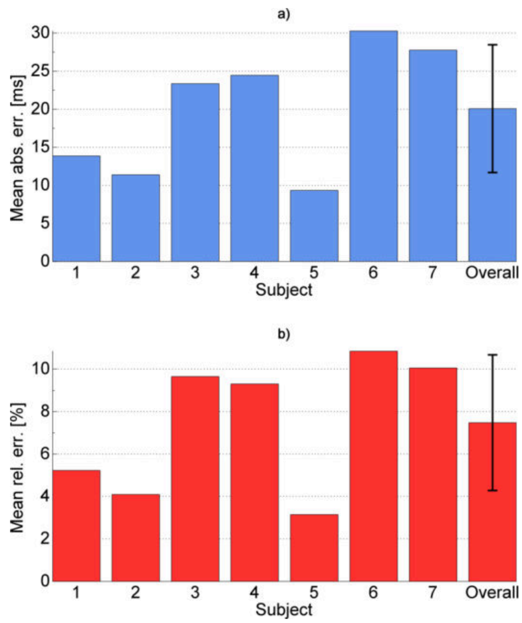

Figure 3. Mean errors measured between the detected beat-to-beat intervals and corresponding referential RR intervals: (a) mean absolute error; (b) mean relative error.

The obtained accuracy parameters disclose more important facts than efficiency. The delays between referential and detected heartbeat time instants are almost the same, about 100 ms. Based on experimental results, the stability of reference-to-detected heartbeat delay, measured by standard deviation, yields around 50 ms, which can be considered acceptable. Acceptance of the delay variance can further be verified when comparing detected beat-to-beat intervals to referential RR intervals, where overall mean absolute error equals 20.05±8.38 ms and overall mean relative error 7.47±3.19%.

Thus, the proposed approach showed satisfactory results even when detecting heartbeats with highly variable heart rate from optical interferometric signals. However, the approach has some disadvantages, such as quite a high computational complexity which is directly related to grid resolution of two-dimensional histogram (values of parameters N_x and N_y). This makes proposed approach less convenient for real-time heartbeat detection. Another drawback can be recognized in the need for optimal parameter selection which should be problem independent. While selecting parameters N_x and N_y, a tradeoff between coarser and denser grid is looked for in order not to make the resolution too low and not to increase computational complexity too much. Same conclusions can be made for other two parameters, namely smoothing parameter λ and threshold p.

Finally, based on the obtained results we expect the proposed approach could be used not only for heartbeat detection from optical interferometric signal, as explained in this paper, but could also be used by other multimethod-based approaches for unobtrusive heartbeat detection, i.e. by ballistocardiography, phonocardiography, etc.

V. Conclusion

In this paper, a multimethod procedure for optimization of detected heartbeat instants was proposed. The approach proved efficient on the optical interferometric signals acquired in experimental protocol with 7 subjects, and shows great potential for further improvements of its accuracy and efficiency.

Further research will focus on lowering standard deviation of reference-to-detected delays and reducing errors between consecutive detected heartbeats and corresponding referential RR intervals, hand in hand with lowering of computational complexity in order to make proposed approach suitable for real-time processing.

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