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Sensing and Signal Processing for Unobtrusive Cardiac Monitoring Utilizing Ballistocardiography

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Home monitoring and telehealth regimens are expected to play a pivotal role in the future of healthcare by enabling an early detection of deteriorating patient conditions and allowing physicians to intervene with proactive instead of reactive treatment measures. Unfortunately, current clinical measurement modalities, such as the electrocardiogram (ECG), are impractical for monitoring health status of patients over extended periods of time. A promising alternative for unobtrusive long-term cardiac monitoring is based on recording minute vibrations of the body caused by the mechanical activity of the heart, the so called ballistocardiogram (BCG). Ideally, this is achieved through sensors integrated into the patient's environment, for instance, by instrumenting the mattress or the frame of a bed to record the motions of the person lying in it. However, BCGs recorded by such sensors are inherently unpredictable in their signal morphology since, in addition to the cardiac activity itself, numerous uncontrollable external influences affect the measurement. Therefore, robust signal processing algorithms are essential to enable meaningful applications of this technology.

This work covers substantial contributions to the field of BCG-based unobtrusive cardiac monitoring which range from a novel sensing principle and sensor design, through robust signal processing methods for sensor fusion and beat-to-beat heart rate estimation, to machine learning algorithms that automatically detect a prevalent type of arrhythmia (atrial fibrillation).

In particular, an optical BCG sensor concept based on the propagation of near-infrared (NIR) light through a regular mattress is introduced. The operating principle of this novel type of sensor is modeled and simulated using a Monte Carlo approach. Furthermore, a prototype of the sensor array is presented and successfully validated using a new mechanical test rig.

Moreover, a general framework for the robust estimation of beat-to-beat heart rates is developed and successfully applied to BCGs. It relies on a new lag-adaptive windowing approach to estimate the fundamental frequency of the signal with beat-to-beat resolution using three time-domain estimators such as the autocorrelation. Bayesian fusion is used to derive a final estimate from the different estimator outputs. In addition to operating on a single signal, the method is extended to support the fusion and joint processing of multiple signals acquired by multi-channel sensor arrays or even by different types of sensors. The developed single- and multi-channel algorithms are evaluated and compared using two sets of BCG data containing a joint total of over 1.1 million heart beats. While the proposed method allows reliable and accurate beat-to-beat heart rate estimation even from single-channel BCGs, accuracy and coverage are shown to further improve when fusing multiple BCG channels. Moreover, the agreement between heart rate variability (HRV) parameters derived from BCG heart rates and an ECG reference is investigated and shown to be good.

Finally, the automatic detection of atrial fibrillation (AF) episodes in BCGs is discussed. Based on a time-frequency analysis of BCGs containing AF episodes, suitable time-domain and time-frequency-domain features for the characterization of AF and normal sinus rhythm are developed. Seven different machine learning algorithms are each combined with a mutual-information-based feature selection approach to automatically detect AF epochs in BCGs. A clinical study to evaluate these classifiers is presented. The results indicate that, with the right set of features and algorithms, automatic classification of atrial fibrillation epochs in BCGs is indeed feasible with high sensitivity and specificity.