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研究課題名（和文）Development of locally-focused noise reduction technique for the green light photoplethysmogram based on its local chaotic characteristics

研究課題名（英文）Development of locally-focused noise reduction technique for the green light photoplethysmogram based on its local chaotic characteristics

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研究成果の概要（和文）：光電脈波（PPG）は、心拍数と酸素飽和度の計算に広く使用されている信号です。別の用途の可能性を秘めているが、信号中のノイズはそれに対する高度な分析方法の適用性を制限している。ノイズを低減するため、ＰＰＧの複雑な特性を保持する方法が必要である。PPGの力学を理解することは、そのような方法を開発するためのキーファクタです。
本研究では、異なる条件下多数のPPGデータを収集し、非線形力学方法で、このPPG信号を分析した。解析の結果により、信号がカオス的力学特性を持ち、その本質的な動的要素（鞍点）を見つけられた。濾過効果の観点からPPGの力学特性を調べて、ノイズ混入の情報に基づいて予測方法を提案した.

研究成果の学術的意義や社会的意義
Green light PPG widely used in wearable devices was investigated. Understanding of dynamical characteristics of green PPG and discovering its dynamics essential element was achieved for the first time. This can help to promote further applications of the green PPG in the health monitoring area.

研究成果の概要（英文）：The photoplethysmogram (PPG) is the signal widely used for heart rates and oxygen saturation calculations. It has the potential for other applications, but the presence of the noise in PPG data limits the applicability of advanced analysis methods to it. Therefore, the noise reduction method which would reduce the noise and unlike conventional methods preserve complex dynamics of the PPG is necessary. Understanding of the PPG dynamics is the key- factor for the development of such a method.
During the research period, the large number of the PPG datasets were collected in reference conditions and under the influence of external factors. These data were analyzed by the methods of nonlinear dynamics. It was discovered that the investigated signal has chaotic dynamics and its essential dynamical element was found (saddle point). PPG dynamical characteristics were investigated in terms of filtration effects. The method of prediction relying on noise contamination information was proposed.

研究分野：応用数学

キーワード：deterministic chaos　photoplethysmogram　signal processing　nonlinear dynamics　noise reduction

１．研究開始当初の背景

Human photoplethysmogram (PPG) is widely used and well investigated in terms of estimation of heart rates and oxygen saturation. However, it has the potential for a variety of other applications for human physiological and mental health monitoring. Presence of experimental noise in the data, as well as lack of understanding of the PPG dynamics, are the factors that limit further development of PPG applications. Achievement of a deeper understanding of the PPG dynamics properties could lead to the development of new applications as well as provide key-information for coping with the noise contamination issues.

２．研究の目的

Purpose of this project was a detailed investigation of dynamical properties of commonly used in wearable devices green light PPG. And after that, based on the obtained PPG characteristics information to approach the development of noise reduction method that, unlike conventionally used methods, could reduce the noise with the preservation of the properties of the original signal dynamics.

３．研究の方法

The PPG data in this study were collected by Arduino based PPG recording device with green LED PPG sensor. Data collection was conducted in a reference environment and under the influence of external factors, such as high temperature and humidity. PPG signal dynamical characteristics, such as determinism, predictability, trajectory divergence, and chaoticity were estimated by methods of nonlinear time series analysis. Additionally, the effects of conventional filtration methods application on these characteristics were evaluated. An approach towards the development of methods that can improve noise reduction in the signal while preserving its complex dynamics was conducted based on the obtained PPG properties, in particular, information on the local determinism changes due to the noise contamination was employed as an input factor for the prediction.

４．研究成果

During the research period a large number of the green light PPG signal datasets was collected. The data were recorded under the reference conditions and with the influence of external factors such as high environmental temperature and humidity to evaluate its effects on the PPG dynamics. All the data sets were analyzed by the method of nonlinear time series analysis. The following results were obtained.

(1) Unlike the conventionally used for decades and well-studied in many aspects near-infrared (NIR) PPG, the dynamics of introduced in recent decades green light PPG (gPPG) was not sufficiently investigated so far. Therefore, the dynamical characteristics of all the collected gPPG data were analyzed by methods of nonlinear time series analysis. Firstly, possible gPPG dynamics was reconstructed by the time-delay reconstructed method. Figure 1 demonstrates an example of the gPPG signal’s time-delay-reconstructed trajectory. Then the determinism, trajectory divergence, predictability, and the chaoticity of the data were estimated. Additionally, green and NIR light PPG characteristics were compared to clarify whether the gPPG signal might be suitable for applications in which the NIR PPG was previously proven useful and promising. The results demonstrated that gPPG dynamics is chaotic, and its properties indicated the greater complexity of the gPPG signal compared with the NIR PPG signal. In addition to the understanding of the fact that the gPPG signal is chaotic, it can also be considered that gPPGs can be valuable not only for heart rate estimation, as they have thus far been used, but also, using nonlinear time series analysis, for NIR PPG applications such as mental and physiological health monitoring. These applications involve analysis of chaotic characteristics that are similar to those of gPPGs. The obtained results improve the understanding of the PPG signal dynamics as well as its waveform creation process in general and the gPPG signal in particular, and emphasize that the gPPG signal can be promising in applications of the rPPG signal, due to their properties similarities.

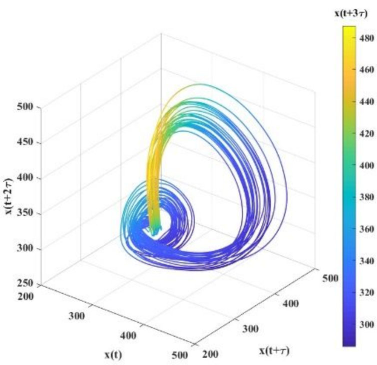

Fig. 1. An example of time-delay reconstructed trajectory for the gPPG.

(2) For the chaotic dynamics, it was previously reported that the noise effect is more significant in the vicinity of equilibrium points. As the results of this study revealed

chaotic nature of the gPPG, effects of noise on its dynamics could be better understood if the location if gPPG ’s equilibrium points would be known, as well as it could improve one’s understanding of the gPPG dynamics itself.

In this part of the study, methods of Morse decomposition were applied to gPPG signal data. The obtained Morse sets, as well as qualitative and quantitative computation results, demonstrated evidence of the existence of a saddle equilibrium in the slowly progressing part of PPG signal. Fig. 2 demonstrates speed distribution along part of the time-delay-reconstructed gPPG trajectory, and the candidate set that is expected to contain saddle equilibrium. The analysis was performed for the subjects with age varying from 21 to 56 years old, and the results were found to be consistent regardless of the subjects’ ages.

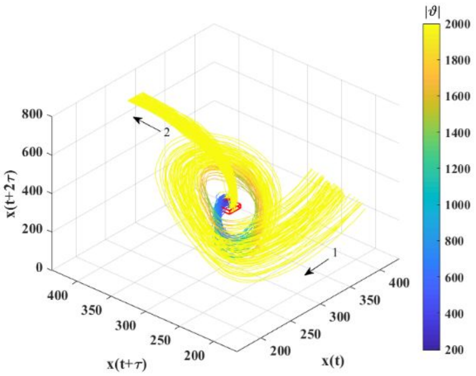

Fig. 2. An example of the trajectory speed distribution along the time-delay reconstructed gPPG trajectory, and the location of the candidate set.

(3) An additional study was conducted on the gPPG data recorded from greenhouse workers in the hot and humid environment to identify the temperature effect on the PPG dynamics and possibility of the observational noise level changes due to the external factors. The results of comparison between characteristics of the reference data and the data collected in hot temperature environment demonstrated that the trajectory divergence characterized by the Largest Lyapunov Exponent and the determinism measure expressed by the Wayland test translation error has the potential to distinguish difference in the gPPG signals obtained from healthy greenhouse workers performing operations in normal and hot working environments. Therefore, these indexes are potentially useful for greenhouse workers’ health monitoring applications.

(4) An additional study was conducted on the imaging PPG as an example of extremely noise contaminated data to evaluate the possibility of its dynamics reconstruction and observational noise reduction. In this part of the study, a data-driven data extraction approach that makes it possible to obtain time-delay-reconstructed imaging PPG trajectories was demonstrated. The approach was based on the combination of data extraction from the original video source, the sequence of interpolation and then filtering steps. As a result, it was possible to reconstruct imaging PPG trajectories. According to the results of the Wayland test, obtained time series might be recognized as noise contaminated deterministic signal. However, since the amount of noise remained considerable, further study is required for decreasing the amount of noise along the reconstructed trajectory prior to the application of other analysis methods. The obtained results are valid for various visible light sources, which makes it useful for further studies involving imaging PPG signals.

(5) The modification of the deterministic nonlinear prediction method that accounts information on the determinism level was proposed. The level of the determinism and therefore the noise contamination was estimated by the local Wayland test translation error. The value of the translation error was employed as weight information for conducting weighted prediction. The results demonstrated certain improvement in the prediction quality for part of the reference PPG data, however stable improvement for every investigated gPPG data set (despite the age and others conditions) was not identified, therefore the further method modification is needed to ensure its applicability for the wide range of the gPPG data.

５．主な発表論文等

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６．研究組織

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