学 位 論 文 要 旨

Study on Chaotic Behavior of Human Photoplethysmogram by Comprehensive Nonlinear Time Series Analysis
生体脈波のカオス挙動に対する包括的非線形時系列解析に関する研究

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Significant effort in the area of health monitoring has been made over the last few decades. Many studies have investigated the correlation between biological signals produced by the cardiovascular system (CVS) and patient health conditions, and obtained indexes identifying various diseases or their states. The photoplethysmogram (PPG) is one of the widely used techniques in medical settings and sports equipment to measure biological signals. It is recognized that the PPG, which can be defined as the continuous recording of the light intensity scattered from a given source by the tissues and collected by a suitable photodetector, can provide valuable information about CVS performance [Allen, 2007]. However, PPG dynamics is not yet fully understood. The PPG is measured noninvasively by inexpensive and simple to use pulse oximeters, and this makes it quite useful for health monitoring applications.

This study sought to investigate the underlying dynamics of the PPG signals from healthy young human subjects. In previous studies the PPG was claimed to be driven by deterministic chaos [Tsuda, 1992, Sumida and Arimiru, 2000]; however, the methods applied for chaos detection were noise sensitive and inconclusive. Therefore, to reach a consistent conclusion it is important to employ additional nonlinear time series analysis tools that can test different features of the signal's underlying dynamics. In this thesis, a comprehensive set of nonlinear time series analysis methods, including time delay embedding, embedding dimension, largest Lyapunov exponent, deterministic nonlinear prediction, Poincaré section, the Wayland test and the method of surrogate data were applied to the PPG time series to identify the unique characteristics of the PPG as a dynamical system. Results demonstrated that PPG dynamics is consistent with the definition of chaotic movement, and its chaotic properties showed some similarity to Rössler's single band chaos with induced dynamical noise. Additionally, it was found that deterministic nonlinear prediction, Poincaré section and the Wayland test can reveal important characteristics

about the PPG signal and therefore these methods will be important tools for theoretical and applied studies on the PPG.

Despite the topological similarities between Rössler's single band chaos and the PPG, the declining trend of their short-term deterministic nonlinear prediction was considerably different, which gave rise to new questions. One of them is related to the rapid decline of predictability performance in the very short range, although in the longer range high performance was sustained; another question is connected with the considerable fluctuations of prediction performance indexes. Therefore, particularly careful attention was paid to the short-term prediction properties of the PPG. Global (related to overall trajectory) and local (in a fixed region on the reconstructed trajectory) predictions were conducted and found to be significantly different. These findings illustrated the variation of the dynamic properties between the local and global levels. Additionally, similarities in the short-term prediction properties were found between the PPG and Duffing's forced oscillator in the chaotic regime. These results emphasized the importance of comparative investigation of the PPG; in addition it identified a new approach for local dynamics investigation that may be promising for further application studies.

Nowadays numerous advantages of wireless and wearable sensor technology have made it extremely useful and promising for various applications in the agriculture and food industries. However, there is still a shortage of techniques to deal with farm workers' health monitoring in the agricultural industry. Therefore, the last part of this study sought to investigate the effect of tractor noise on the CVS of farm workers by the PPG technique. Fourier transform and nonlinear time-series analysis methods, such as time-delay embedding and the Wayland test, were applied to the PPG signal to analyze differences in CVS performance arising upon exposure to levels of tractor noise corresponding to low, medium, and high tractor engine speeds. Results showed that the ratio of two significant component frequencies obtained by Fourier analysis and the Wayland test translation error can distinguish differences in the PPG signal that arise under noise exposure. Additionally, the translation error was less dependent on the subject than the frequency ratio, which may make it a useful index for application to real-time health monitoring of farmers.

This study demonstrated that comprehensive nonlinear time series analysis has high potential for effective and reliable PPG dynamics investigation and its application to the PPG can not only improve our understanding of PPG dynamics, but also stimulate the development of new PPG signal based applications related to health monitoring in general and particularly in the agriculture industry.