engineering proceedings

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Proceeding Paper

Integration of a Novel Clustering Algorithm and Multiple Sensors to Achieve the Noise Cancellation of Heart Rate †

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† Presented at The 11th International Electronic Conference on Sensors and Applications (ECSA-11), 26–28 November 2024; Available online: https://sciforum.net/event/ecsa-11.

Abstract: Many wearable devices are commonly used to measure vital signs, heart rate is the most frequently monitored physiological information. Due to the weak signal strength of heartbeats, capturing these signals presents a significant technical challenge. Therefore, this paper adopts a non-invasive wearable device for detecting heartbeats. A wearable device is constructed using three polyvinylidene fluoride (PVDF) piezoelectric film sensors, placed at the three endpoints of an equilateral triangle with a side length of 3 cm, and positioned near the heart to detect heartbeat signals. The multiple sensors in this wearable device utilize the vibration signals to cause deformation in the PVDF piezoelectric film, generating voltage amplitude to represent the magnitude of the vibrations. Since the sensors are very sensitive to detect vibration signals, both physiological signals and surrounding noise are detected when the heart beats, resulting in a low signal-to-noise ratio (SNR) for heart rate signals and significantly increasing the chances of incorrect heart rate interpretation. In this paper, to improve the SNR, not only is hardware circuit design employed to amplify the signals and eliminate high-frequency noise using a low-pass filter, but a novel clustering algorithm is also used to group and classify the datasets by the three sensors. Irregular signals that deviate from the clusters are treated as noise, thereby eliminating noise from the signals and improving the quality of the physiological heart rate signals. According to the experimental results, the SNR of the heart rate signal after noise cancellation can be increased by 7 dB, and the accuracy of heart rate signal recognition can reach 98.46%.

Keywords: non-invasive; PVDF; clustering algorithm; SNR; peak detection

Citation: Ni, J.-C.; Yang, C.-S.; Wang, Y.-T. Integration of a Novel Clustering Algorithm and Multiple Sensors to Achieve the Noise Cancellation of Heart Rate. *Eng. Proc.* **2024**, *6*, x. https://doi.org/10.3390/xxxxx

Academic Editor: Jui-Chung Ni

Published: 26 November 2024

1. Introduction

Heartbeat rate is one of the most important human physiological signals. It is generated by the operation of the heart and gives important information about health, physical activity and psychological state and allows early diagnosis of heart diseases. The World Health Organization (WHO) states that 17.9 million people died from cardiovascular diseases (CVD) in 2019. 85% of these deaths were due to heart attack and stroke. Monitoring the status of CVD's gives information about patients' health status and can be used to decrease the death rate.

A Heart Rate Monitor (HRM) records the pulse rate and is used in personal daily health status indicators to continuously monitor the health of the elderly or patients [1] and during training for sports [2]. It uses a sensor to detect a biological signal and a signal processor [3].

Cardiac auscultation is used to diagnose heart disease. The systole and diastole of the myocardium opens and closes a valve so the impact of the blood flow on the wall of the ventricle and the wall of the aorta creates a turbulent flow. Mechanical vibration is transmitted to the chest through the surrounding tissue and the heart sound can be heard using a stethoscope [4,5]. However, in a normal environment, heart sound signal is one of many different signals, including ambient noise such as respiratory sounds、muscle noise、motion artifacts and frictional noise [6,7]. The intensity of the signals from the body is very low so it is difficult to distinguish heart sounds.

This paper focuses on using multiple PVDF sensors [8] on a wearable device to increase the amount of collected datasets and expand the detection range of the chest area for heartbeats. Additionally, a designed bandpass filter circuit is utilized to eliminate high-frequency noise. The collected datasets are then processed through a novel clustering algorithm [9,10], which removes outlier signals and identifies the true heartbeat signal clusters, thereby improving the accuracy of heart rate calculation.

2. Materials and Methods

2.1. Signal and Noise

In heartbeat detection, besides vital signal, the original heart beat signal mixed a lot of noises as ambient noises and body noises, the approach is therefore to apply a filter circuit and algorithm to suppress noises, SNR quality impacts heartbeat signal's recognition, the relationships among of SNR、noises and vital signal expressed as follows Figure 1.

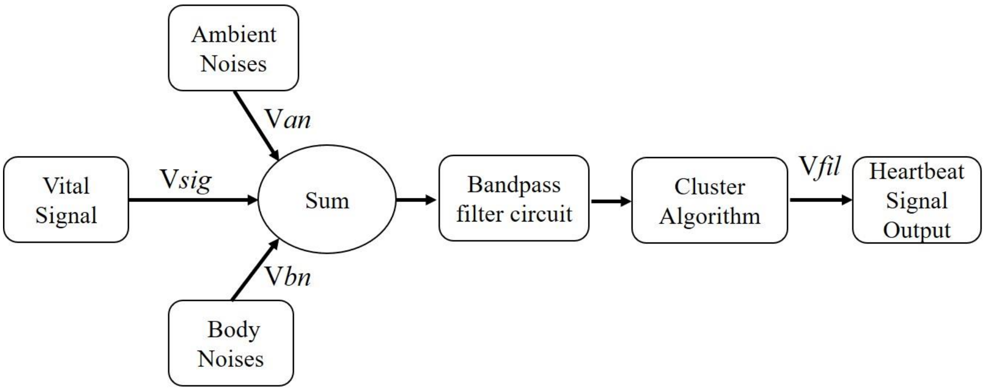

Figure 1. Signal flow chart of the proposed approach.

Here V*sig* and V*bn*/V*an* represent the effective voltage of the heartbeat signal, ambient noise and body noise, V*fil* represents the effective voltage of the filtered signal; Therefore, the higher SNR means that it has less noise to be carried on the heartbeat signal, and the higher valuable contents of signal are mixed in the heartbeat signal.

2.2. The System Block Diagram of Wearable Device

In this paper, it proposed a wearable device and the block diagram of the system structure is shown in Figure 2. There are four units: (1) the Signal Acquisition Unit (2), the Signal Filter Unit (3), the Signal Sampling Unit and the (4) Data Processing Unit in this system.

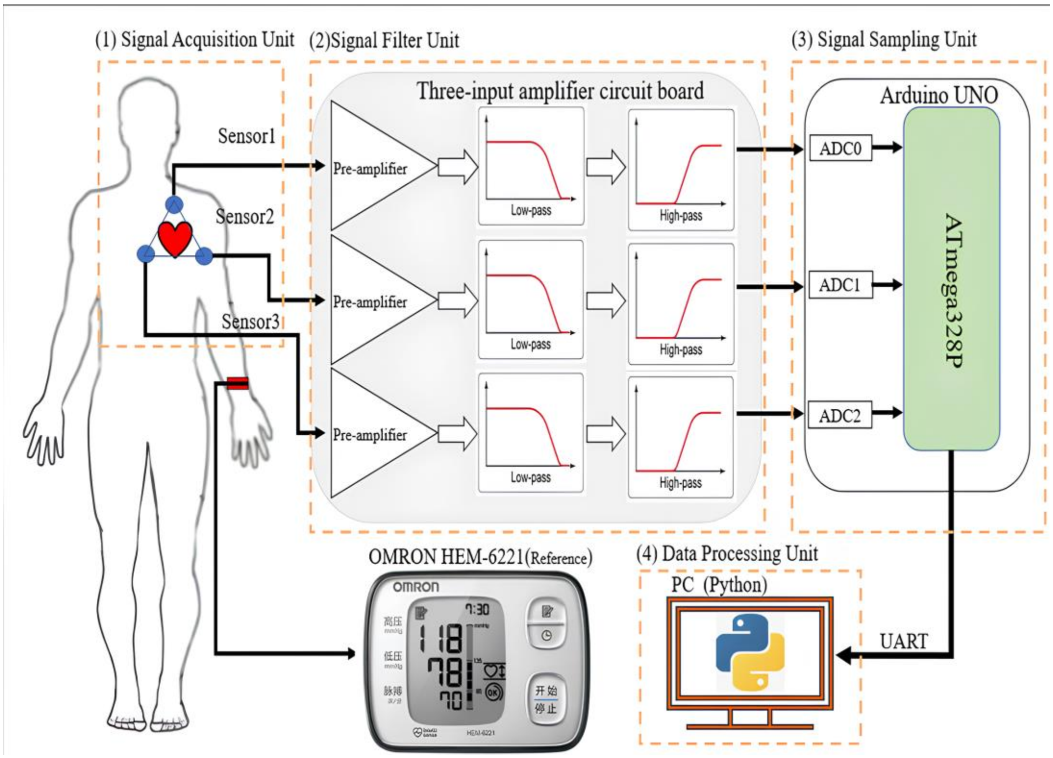

Figure 2. System block diagram of wearable device.

2.2.1. The Signal Acquisition Unit

The Signal Acquisition Unit has three sensors in the wearable device: Sensor 1 (abbreviated as Sen1), Sensor 2 (abbreviated as Sen2) and Sensor 3 (abbreviated as Sen3). The device uses a highly sensitive piezoelectric film to detect slight vibrations. It is arranged in an equilateral triangle with a side length of 3 cm and positioned over the heart to collect heart rate data [11].

This study uses multiple sensors. The differences between a single sensor [12] with multiple sensors are listed in the following:

Multiple sensors have a fault-tolerant mechanism: if one of the sensors is damaged or has poor contact, other sensors work normally.

Easier installation: the distance from the heart to the sensor is inversely proportional to the signal strength so it is easier to obtain the pulse rate signal using multipoint detection.

Stronger anti-noise capability: When the sensing signal features specific noises.

2.2.2. The Signal Filter Unit

The Signal Filter Unit includes a signal amplifier and a bandpass filter for each sensor. The bandpass filter maintains the signal frequency in the range 0.5~200 Hz and frequencies beyond this range are filtered.

2.2.3. The Signal Sampling Unit

The Analog to Digital Converter's resolution of micro controller unit (MCU) is 12 bits, and the sampling rate is 500 Hz, it follows Nyquist Theorem that the sampling frequency must be greater than twice the signal's bandwidth. The communication interval time is 2 ms to ensure that MCU has enough time to save and transmit raw data of heartbeat signal, as shown in Figure 3.

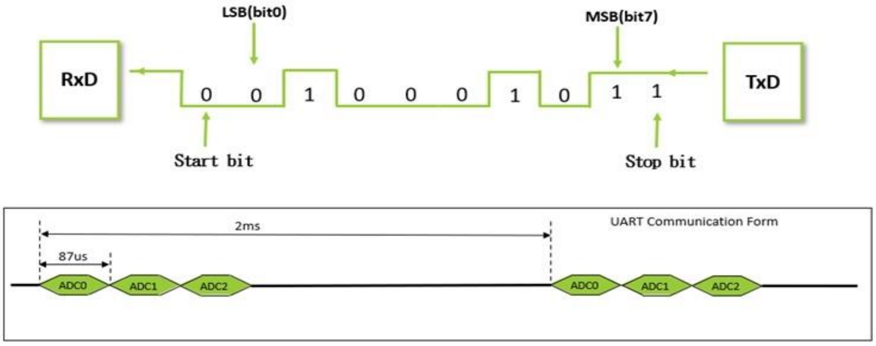

Figure 3. UART communication format.

2.2.4. The Data Processing Unit

The Data processing Unit adopts a novel clustering algorithm as Figure 4 to classify the peak signals and remove peak signals that are far away from the group [13–15] for denoising.

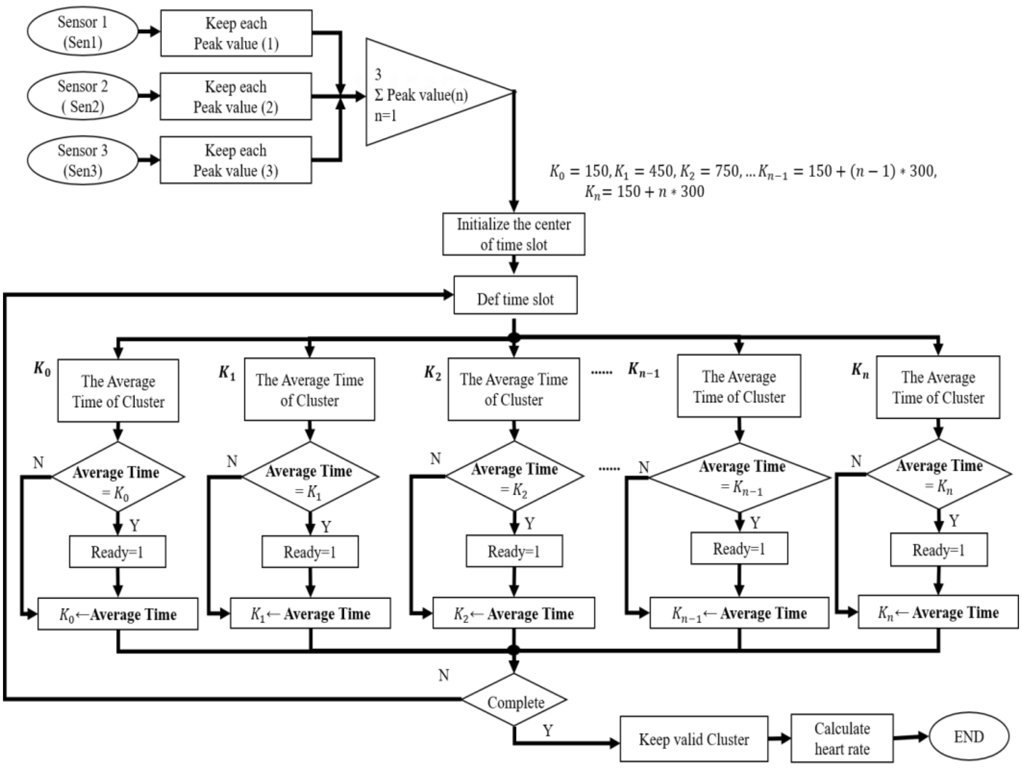

Figure 4. Cluster algorithm flowchart.

The algorithm flow is shown in Figure 4 and has five steps as follows:
Time slot is every 300 ms from K_0 to K_n, and the starting point is from $K_0 = 150$ ms, $K_1 = 450$ ms.

$$n = \text{Signal length(ms)} \div 300\text{(ms)} \tag{1}$$

n: number of time slot

Classify all peak signals from the three sensors under the definition of time intervals. If the peak signal occurs in the interval from 0 ms to 300 ms, it is grouped at time point K_0 and next peak signal that is detected in the interval from 301 ms to 600 ms is grouped at time point K_1. Grouping from K_0 time point is used to sequentially classify all peak signals.

If the average value of the current peak value in each group is not equal to the time point for the group, the original time point is replaced with the average value for the peak signal in the group and the algorithm returns to the previous step. All peak signals are regrouped using the new time point.

When the evolution of the time points for each group no longer changes, the grouping action is terminated and the groups with peak signals of less than three records in each group are removed.

When the best value is determined for each group, the average time for the peak signal time is the center point of the heartbeat time slot and the heart rate is calculated using the time distance between the two center points.

Figure 5(a)/(b)/(c) represent the datasets from each sensor. After applying the algorithm, the peak signals in each sensor dataset are marked with yellow dots. Figure 5(d) combines the peak signals from the three sensors, and the peak signals in each time slot (e.g., k1, k2…) are clearly marked with red dots.

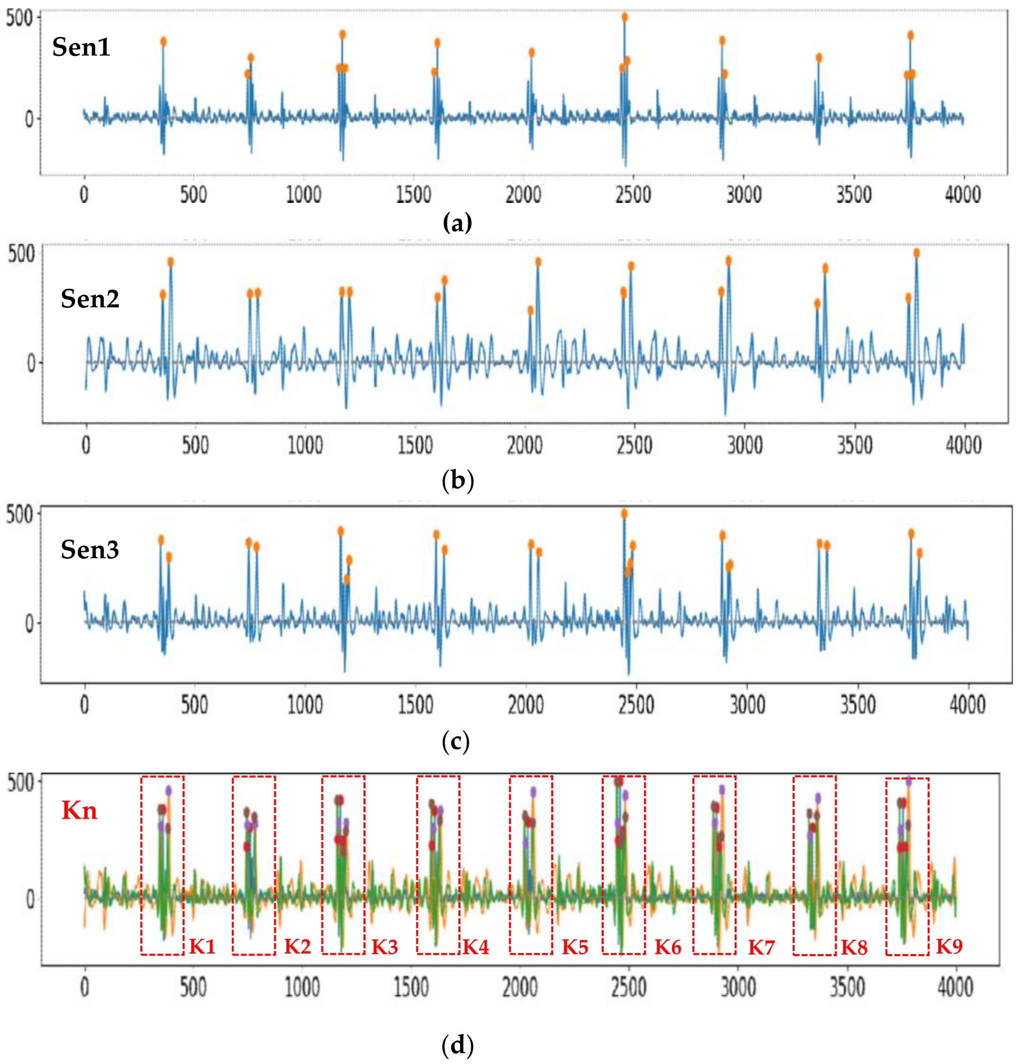

Figure 5. The peak signals of each sensor via Clustering algorithm (**a**) Show all peak signals of Sen1; (**b**) Show all peak signals of Sen2; (**c**) Show all peak signals of Sen3; (**d**) Show all peak signals of Sen1, Sen2, Sen3 during each time slot (Kn).

3. Results

To determine the performance of the system, five adults participated in this experiment. They wore devices for heart rate detection on the chest and were examined in the sitting position. To create a reference, heart rate was measured using a standard medical device (OMRON HEM-6221) to compare with the wearable device. The performance of both devices is very similar and the accuracy of the proposed wearable device is 98.46%, as shown in Table 1. The accuracy of this wearable device is sufficient to measure heart rate and the test result is reliable.

The measurement result in Table 2 shows the original signal quality and the improved signal quality with de-noisy process. The SNR of the signals enhance 7.76 dB on average.

Table 1. Accuracy of HEM-6221 and the proposed wearable device.

Subject	HEM-6221(B.P.M) (Standard)	Proposed Wearable Device (B.P.M)	Accuracy of the Proposed Wearable Device (%)
1	72	72	100
2	83	81	97.59
3	72	72	97.86
4	67	67	99.55
5	78	80	97.34
		Average Accuracy (%)	98.46%

Table 2. Original and improved signal quality

Subject with 3 Sensors	Original SNR (dB)	With Noise Cancellation Method SNR (dB)	Improvement SNR (dB)
1_Sen1	11.54	16.90	
1_Sen2	7.96	12.04	5.2
1_Sen3	12.04	18.06	
2_Sen1	12.04	18.06	
2_Sen2	7.60	16.90	7.5
2_Sen3	4.44	11.48	
3_Sen1	9.54	17.5	
3_Sen2	7.96	14.62	6.5
3_Sen3	13.98	18.84	
4_Sen1	7.96	20.00	
4_Sen2	12.04	21.58	10.4
4_Sen3	6.02	15.56	
5_Sen1	10.46	16.90	
5_Sen2	6.02	16.90	9.2
5_Sen3	6.72	16.90	
		Average Improvement SNR	7.76

4. Discussion and Conclusions

This study proposes a system that adopts a clustering algorithm to suppress noise in vital sign signals. A comparison of the original signal quality and the improved signal quality shows that noise is suppressed, the SNR for the improved signal was 7.76 dB better and the accuracy of heart rate is 98.46%. The better SNR allows more rapid diagnosis and clustering algorithm is a feasible method.

Furthermore, study will use different algorithms to reduce power consumption for the wearable device and detect different vital signs to allow diagnosis of specific symptoms the early prevention of disease in the future.

Author Contributions: Conceptualization, J.-C.N.; methodology, Y.-T.W.; software, Y.-T.W.; validation, J.-C.N.; formal analysis, J.-C.N.; data curation, Y.-T.W.; writing—original draft preparation, J.-C.N.; writing—review and editing, J.-C.N.; supervision, C.-S.Y.; project administration, J.-C.N.; All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.

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