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Non-Contact and Non-Invasive Driver's Monitor Using Microwave Reflectometer

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Abstract—This paper describes the measurement of a driver's instantaneous heart rate corresponding to R-R interval in electrocardiogram and heart-rate variability (HRV) using 24 GHz radar reflectometers. Elimination of the spurious component due to random movement of a driver has been the most difficult problem for microwave measurement. Auto-gain control of the receiver, template matching and cross-correlation technique among multiple reflectometers enable motion artifact elimination, signal peak detection, and data processing for various parameters. The measurement of vital signals is considered useful for predicting the change in a driver's state, such as a heart attack as well as detecting drowsy driving, drunk driving, and fatigue.

1. INTRODUCTION

It is known that a driver's physiological state is reflected by vital signals, such as heart beat (heart rate: HR), respiration, blood pressure, and body temperature. Specifically, HR and its fluctuation can be used for the mental and physical states of drivers. Several methods have been developed such as electrocardiograph (ECG), piezoelectric sensor, ultrasonic sensor, and infrared and microwave reflectometry sensors [1–5]. Microwave reflectometry, especially in larger than 10 GHz region, remotely measures human skin movements when breathing and heartbeat are present [6].

Heartbeat interval is constantly fluctuating due to autonomous nerve activity composed of sympathetic and parasympathetic nerve activities. Time variation can be regarded as the short-term time variation of instantaneous HR, the so-called heart rate variability (HRV). In the frequency spectrum of the HRV, parasympathetic nerve activity appears in the spectral region of 0.15–0.45 Hz (the so-called HF region), and both sympathetic and parasympathetic nerve activities appear in the region of 0.03–0.15 Hz (the so-called LF region) [7–9]. The peak ratio or area ratio of the power spectrum in the LF component to the HF component is often used to evaluate the mental and physical stress conditions. Sympathetic nerve activity increases in a stressful state, and parasympathetic nerve activity increases in a relaxed state. The ratio LF/HF in a stressful state is larger than that in a relaxed state. The coefficient of variation of R-R intervals (CVRR) can also be introduced as one of the indices to evaluate autonomous nerve activity [10, 11].

Conventional electrocardiographic monitoring has been a significant tool for evaluating HR/HRV. However, the evaluation method using ECG seems unsuitable for long-time monitoring, since several electrodes are attached directly to the human body to acquire the data. Specifically, there is some concern regarding the practical application of the ECG system to drivers. Therefore, we propose

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microwave reflectometry as an HRV evaluation method since it is completely noninvasive and feasible even through thick clothing [12]. In this paper, we focus on the real-time evaluation of HR and HRV, which enables evaluation of the driver's mental and physical conditions.

2. REFLECTOMETER SYSTEM FOR VITAL SIGNAL DETECTION

Radar reflectometry has been applied as a means to detect the distance and direction to an object. When the target position changes periodically, we can evaluate the fluctuation frequency from the reflectometry signals. This can be utilized for the measurement of vital signals as a non-contact method. The most common method for vital signal detection is a fixed-frequency reflectometer, since its electronics circuit is rather simple,in low cost, and easy to be approved as a consumer appliance under the Administration of Radio, the Ministry of Internal Affairs and Communications (MIC), Japan [13].

In the initial experiment, 24 GHz radar modules (JRC NJR4265J) are applied to the measurements, since outdoor use is authorized in Japan as a movement body detection sensor when the radiation power is low. The modules are installed in the seat of the chair as shown in Fig. 1. A microwave power is irradiated onto the path of an artery in the thigh of a subject via a patch antenna array. The modules have I-Q terminals. Each signal is input to AD converter to obtain the phase fluctuation due to vital signals.

Recently, we have developed an improved homodyne system as shown in Fig. 2. A microwave

(a) (b)

Figure 1. (a) 24 GHz radar modules and (b) measurement environment at the office.

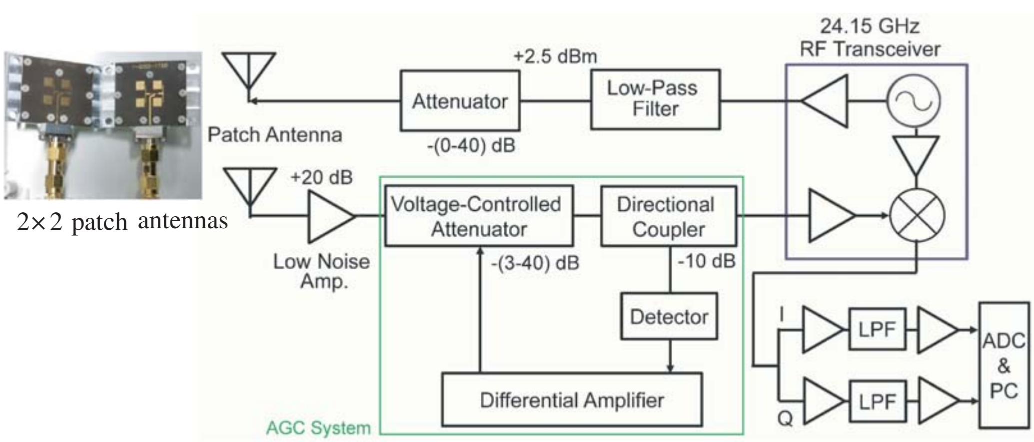

Figure 2. Schematic of the 24 GHz reflectometer with an AGC attenuator.

oscillator is used as both an incident wave and a local oscillator (LO) wave. One of the waves is irradiated onto the area near the human heart or the path of an artery in the thigh via a single patch antenna or a $1 \times 2 \sim 2 \times 4$ element patch antenna array. The directivity of antennas must be selected depending on the position of the measurement. High gain antennas are needed in the case of remote measurement (> 1 m). However, in the present experiment, rather low gain antennas are utilized for the short distance measurement (≤ 5 cm, beam radius is ~ 3 cm at the irradiation position). Since the phase fluctuation must be analyzed, the optical alignment of the radiation beam is not important so long as a sufficient signal to noise ratio is observed. The reflected wave from the skin or the surface of the heart is picked up by an identical antenna and amplified by a low noise microwave amplifier. A voltage-controlled attenuator (VCA) is utilized to control the reflected wave in both static and non-static environments of a human subject. A good signal to noise ratio (SNR) for evaluation of HR/HRV is obtained using this system with an output power of less than -40 dBm (100 nW), which satisfies the condition of weak radio station under the MIC [13].

3. EVALUATION OF HR AND HRV

The HRV is generally obtained from R-R intervals in an ECG. The microwave reflectometer signal includes various fluctuation noises due to random movement of a body surface as well as the respiration component, thus making it more difficult to detect the heartbeat interval corresponding to the R-R interval.

Two methods (algorithms) have been developed to evaluate instantaneous heartbeat interval (heart rate) [6, 13, 14]. One is cross-correlation technique. In this algorithm, a template signal is formed by the arithmetic average of a reflected wave. Then, the cross-correlation function between the template and measurement signal is calculated to obtain a clear waveform for determination of the peak interval. The other is maximum entropy method (MEM) algorithm. The time variation of the heartbeat frequency is evaluated by applying the MEM repeatedly over the short term. The time window is shifted step by step along the temporal axis. The HRV can then be reconstructed once the value of the heartbeat interval is calculated by the inverse of the heartbeat frequency [15].

When the radar reflectometer is applied to the detection of vital signals in a daily life, for example, under sleeping, working, and driving, the real time measurement becomes extremely important. We have developed a new algorithm for real time evaluation of those parameters. One is to measure the time evolution of HR using time-to-frequency spectrum analysis (wavelet transform), and the other is to measure the instantaneous HR (the time evolution of R-R interval) using developed algorithms. The key point of the program is an application of parallel processing of data collection and data analysis.

4. EXPERIMENTAL RESULTS AND DISCUSSION

At first, the demonstration experiment is performed for a human subject working with a PC. The time evolutions of HR and HRV indices obtained by a microwave reflectometer are shown in Fig. 3 for a subject in a relaxed state and a stressful state. The latter case is realized by applying physical stress during a time interval (60–140 sec) shown in the figure. It is seen that the values of HR and LF/HF increase during the stress conditions. We have compared the results between reflectometry data and ECG. It is seen that the values of HR are in good agreement while the values of LF/HF show discrepancy; however, the tendencies of time behavior agree well.

We can summarize the behaviors of the experimental results of HR and LF/HF as:

i) The change rate of HR is less than 2–3% in a relaxed state, and it increases up to 10% or more in a stressful state.

ii) The value of LF/HF is larger in a stressful state than in a relaxed state.

Therefore, the effectiveness of the HR and HRV indices as an evaluation parameter of the human state is identified.

The parameters LF, HF, and CVRR obtained from HRV (HRV indices) can be utilized for evaluation of drivers' mental and physical conditions, such as for detecting drowsy driving, drunk driving, and fatigue, which will be important even for an autonomous car. The real time measurements

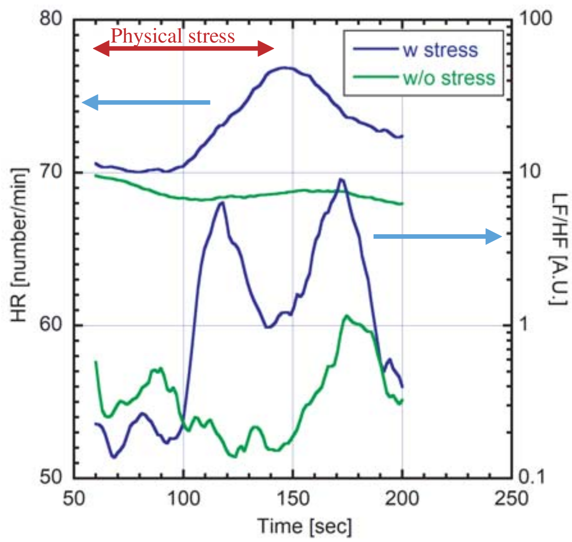

Figure 3. Measurement of the HR and LF/HF for two conditions with and without stress.

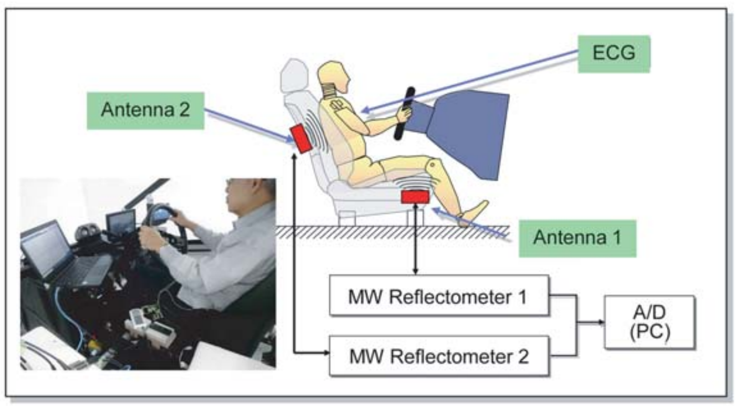

Figure 4. Schematic of the experimental setting and picture photo for the test using a driving simulator.

of HRV indices are performed using a driving simulator with 24 GHz radar modules as shown in Fig. 4. A picture of experiment scenery is shown in the inset of Fig. 4.

A homodyne type I-Q phase detection system with a VCA shown in Fig. 2 is useful for this experiment. Also, the noise components are reduced by calculating a cross-correlation function between two reflectometer signals. Two microwave reflectometers are installed in the seat and behind the driver's seat. The main test conditions using a driving simulator are selected as follows: i) idling state without movement, ii) highway driving, iii) city road driving, and iv) suburban road driving.

As the first step, the time evolution of the heart rate spectra is obtained by using wavelet transform for an idling case, which is shown in Fig. 5. The analysis is performed in every fixed time interval (5–10 sec) and displayed on a PC continuously. Two microwave sensors are utilized in this measurement. The cross correlation between two sensors is also calculated. The difference of the peak values of wavelet spectra between microwave reflectometry and ECG signals (called error rate assuming the ECG value is correct) is shown in the top right trace. The error rate seems less than 1–2%. A good agreement between microwave and ECG is obtained.

Figure 6 shows examples of the error rate for idling and highway driving. The error rate is less than 1–2% for the idling case. For the highway driving, there is a large error rate at a start-up time (during an acceleration phase) and at 160–170 sec during passing front vehicle. However, the error rate is less

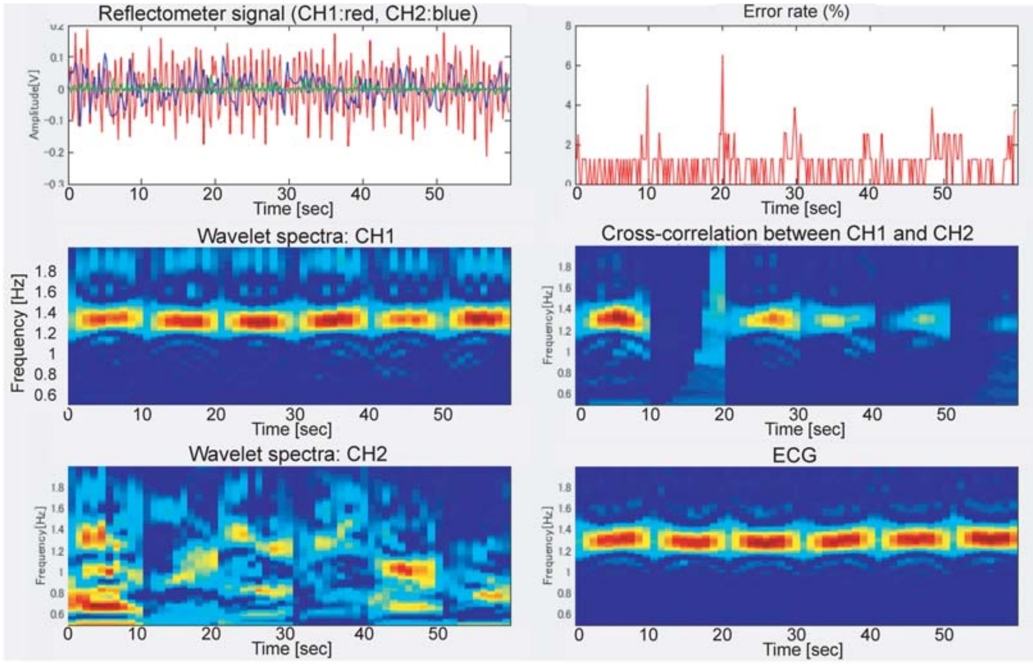

Figure 5. Real-time measurement of the HR spectra: (top left) waveforms of reflected signals, (top right) displacement rate of the peak value between microwave ch1 and ECG spectra, (middle and bottom) wavelet transform of microwave and ECG signals.

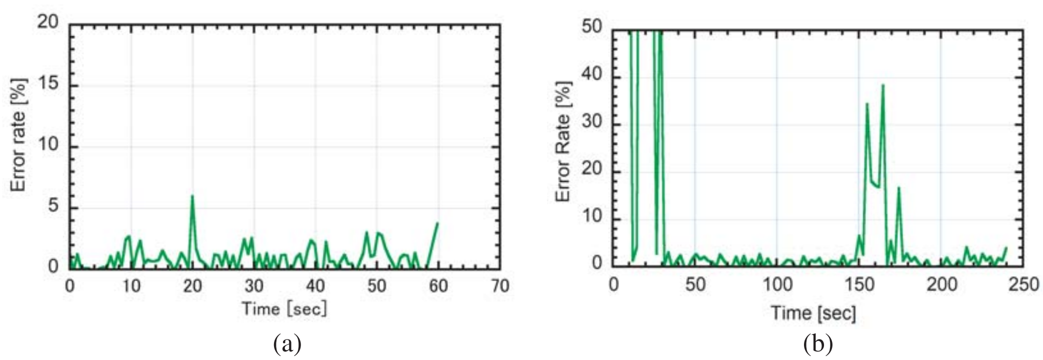

Figure 6. Error rate for the condition of (a) idling and (b) high-way driving.

than a few percent in another period. We can conclude that the HR measurement using reflectometry is reliable as a driver's monitor.

Figure 7 shows the results of HR and HRV obtained from a subject driving on a highway road. The values of HR agree with each other between microwave and ECG measurements. The CVRR shows discrepancy in the initial time ($t < 85$ sec). However, the values come to agree with each other between microwave and ECG especially in the time behavior. The LF/HF shows a similar time behavior although the absolute values are different. The value of LF/HF is relatively high probably due to high-speed running. The bottom of Fig. 7 shows time evolution of LF component corresponding. Note that the LF components agree well between microwave and ECG measurements. On the other hand, the HF components show large discrepancy, although the time behaviors show some similarity.

For the case of city road driving shown in Fig. 8, the values of HR and LF/HF do not agree in the initial time ($t < 92$ sec) since there are many traffic signals and turns in the driving course. After $t > 92$ sec, the simulator moves to suburban. Then the values become close to each other. In the

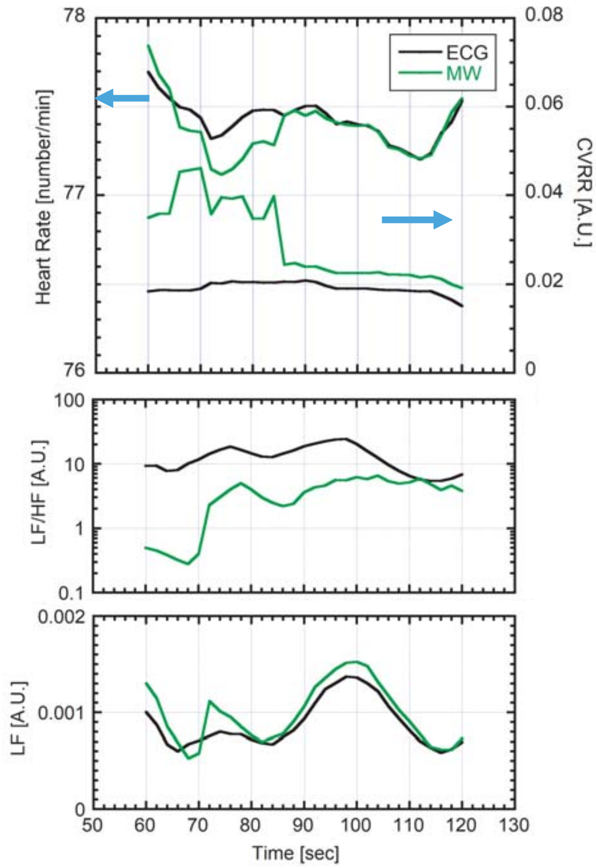

Figure 7. The values of HR/HRV: highway road.

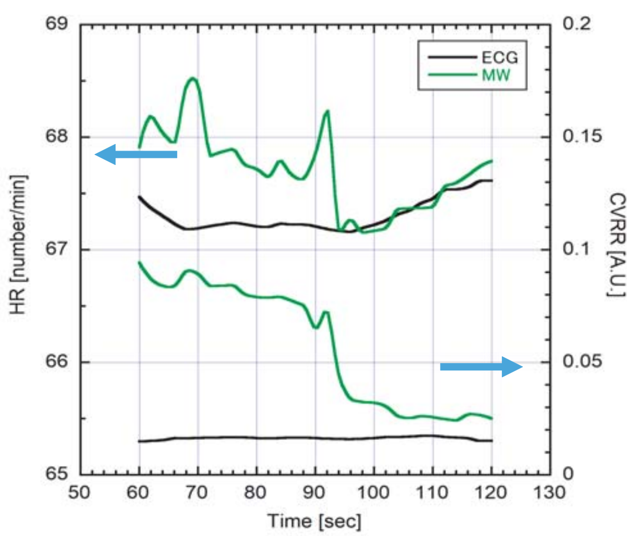

Figure 8. The values of HR/HRV: city road.

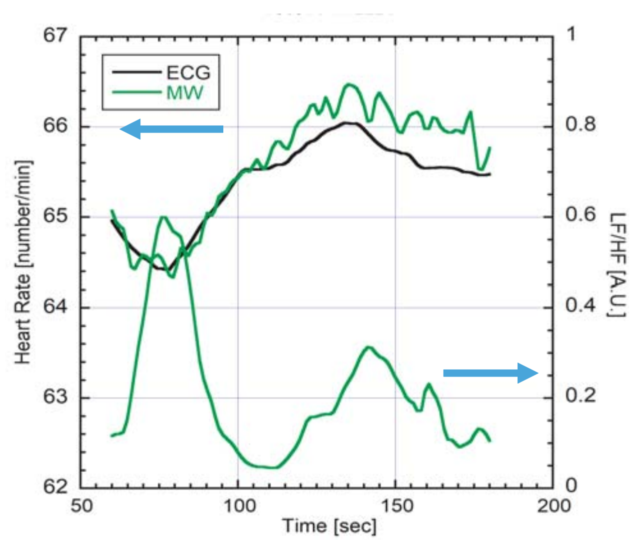

Figure 9. The values of HR/HRV: suburban road.

previous experiment using a 10 GHz reflectometer system, the value of LF/HF has the similarity within ±30% or more [6, 14]. However, the 24 GHz system introduces much more discrepancy. This is caused by large phase fluctuations in the high frequency component due to short wavelength. The body movement will introduce large high frequency noises.

Figure 9 shows the results for suburban road. Note that the HRs agrees with each other between ECG and microwave within 1%, and the LF/HF is low compared with highway driving, which probably means that the driver is in a relaxed state.

The behaviors of the experimental results of HR and HRV during driving are summarized as:

i) The HR measurements agree well between microwave and ECG for most of the driving conditions.

ii) The time behaviors of the HRV indices show similarity although the absolute values show some discrepancy.

iii) The LF components agree well between microwave and ECG measurements. On the other hand, the HF components show large discrepancy. However, the time behaviors show some similarity.

We can conclude that the 24 GHz reflectometer system together with HR and HRV evaluation algorithm can be applied to a driver's monitor at least on a highway and suburban roads.

5. CONCLUSIONS

A radar reflectometer is applied to the biological (vital) signal detection. We have proposed new signal processing techniques as well as system improvements such as cross-correlation between two reflectometers and I/Q detection with voltage controlled attenuator.

By combining the microwave reflectometer and proposed algorithms, the time behaviors of HR and HRV indices (LF, HF, and CVRR) can be obtained in real time. This potential will become useful for evaluation of subject's mental and physical states under driving. In the present paper, the usefulness of microwave reflectometers for non-contact and non-invasive HR and HRV measurements is described. However, there are still important issues. For example, the usefulness of the HR and HRV measurement relating to the stressful state and the relax state is also an important issue. We will leave this for future study.

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