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Investigating a 24 GHz CW-Radar for Non-Contact Vital Sign Sensing in Construction Machine Cockpits to Increase Safety on Building Sites

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Abstract

The US-construction industry sector in 2018 had about 4.5 % of U.S. workers, but 19.1 % of the fatalities - the largest number [1] of fatalities reported for any industry sector [2, 3]. In this context, transportation incidents with heavy vehicles and aging workers over 55 years have the highest fatal event accounting in respect to selected events and demographic characteristics [3]. Therefore, research is underway to measure the health condition of the driver in the construction machine cockpits unobtrusive and non-interfering with their activities. Generally, in research this attempt can be divided into those based on image analysis of camera images, those equipped with wearable sensors, and the method of incorporating sensors in the workers environment, e.g. chairs, controllers, steering wheel, etc. There are various ways to incorporate sensors into the chair [4]. E.g. one of the authors is also trying to extract the driver's heartbeat and respiration information with capacitive electrodes and a pressure sensor built into the seat [5]. This paper focuses on a biometric driver seat concept based on Vinci and Leonhardt [6] using a 24 GHz CW-Radar sensor module to monitor the driver’s health status. The radar sensor signal carries information about the respiration, heartbeat and motion signals of the driver by evaluating the phase-shift of the reflection wave. To separate the respiration-signal from the heartbeat-signal a digital low-pass filter with a cutoff frequency at 0.5 Hz is used. The driver’s respiration rate (RR) is determined by a maximum peak detection in the frequency-domain of the radar signal. The heart rate (HR) is obtained in the time-domain by a heartbeat count estimation. The elimination of random body movement artefacts was not examined in this work. The authors’ objective by this work is to improve safety on construction sites, via the proposed biometric driver seat concept, by early identification of potential health hazards of the driver. For this objective, it is necessary that the detection of human vital signs inside of the cockpit of construction machines will become a part modern driver assist and safety systems in future.

Keywords: biometric driver seat, unobtrusive driver health state monitoring, non-contacting vital sign sensing, CW-Radar Sensor

1. Introduction: A biometric driver seat concept

Working on construction side safely, means according to Haslam et al. [7] to work efficiently. Therefore, it is important that construction works are well rested and healthy. However, Haslam et al [7] confirms that for operatives are only rarely any effective pre-employment health surveillances or screenings.

Also [8] found that there is only little possibilities given for health monitoring on construction side and that there is the link between “occupational health” and “health and safety departments” is missing. Therefore, in this paper, the authors present the concept of a biometric driver seat for contact free measurement of the vital sign parameters of construction machinery drivers. This approach can enable a health data screening in order to increase safety on construction side. For this purpose, a capacitive electrocardiograph for ECG, HR, HRV detection and a 24 GHz CW-Radar for the detection of the RR and PTT (pulse transit time) are used. The sensors are arranged as shown in Figure 1. The cECG electrodes (green) consist of a conductive silver-coated fabric and are sewn onto the backrest of the driver seat.

The electrodes are placed according to the Einthoven 1 arrangement in order to obtain the largest possible amplitude signal of the QRS complex. The seat under the driver's buttocks acts as a ground plane. A conceptual implementation of the ECG unit is presented in Pehr et al. [9] . The 24 GHz CW-radar (yellow) is installed at the chest level of the backrest to monitor the driver’s respiration frequency and heartbeat signal. Radio signals in the 24 GHz range can penetrate foams and clothing with low attenuation and get reflected/absorbed by the human body. A second 24 GHz CW-radar sensor is attached at the end of the biometric driver seat for pulse wave detection at the artery in the thigh. In combination with the cECG sensor, the PTT can be determined, which allows an indirect conclusion about the driver's blood pressure.

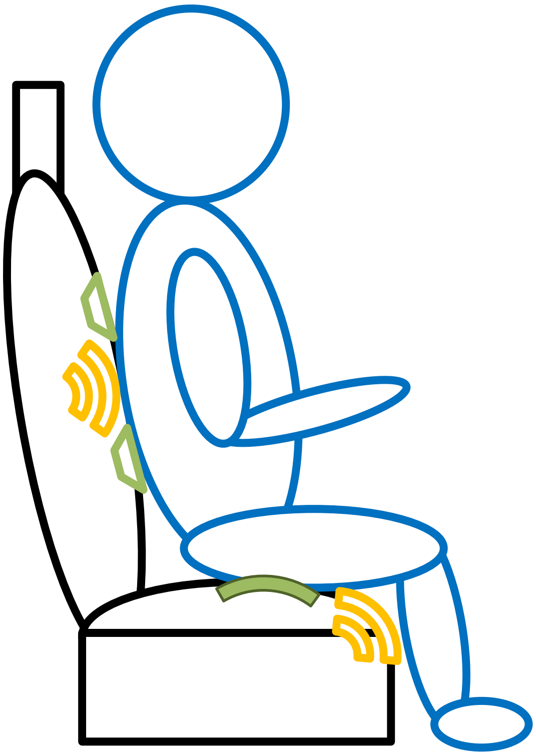

Figure 1: cECG electrodes (green) and Ground plane (green) place at the backrest and biometric driver seat bottom to measure ECG, HR and HRV through the drivers clothing according to Einthoven 1. Cardio Radar Sensor (yellow) is placed at the biometric driver seat backrest to measure RR and HR. Pulse Radar Sensor (yellow) is place at the end of the biometric driver seat to measure the PTT and BP in combination with the capacitive ECG.

2. Material and methods

The implementation of RR and HR detection of the proposed biometric driver seat is carried out by a 24 GHz CW-radar sensor. Therefore, we used the IPS-154 sensor from the company InnoSenT as shown in Figure 2. It provides an EIRP output power level of 16dBm/40mW (average) and 20 dBm/100mW (maximum).

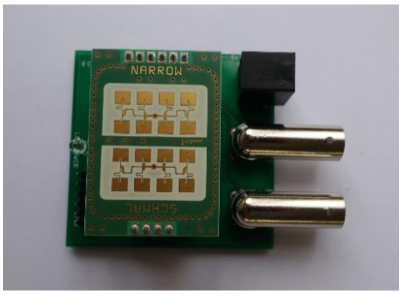

Figure 2: IPS-154 CW-radar sensor from the company InnoSent.

The concept of the CW-radar sensor is shown in Figure 3. The transmitted wave of the 16-element patch antenna array is reflected from the back of the driver, which movements induced by the heartbeat, breathing and random movement artefacts generate a phase shift Δφ in the incident wave. The phase shift is a result of the doppler effect which comes into account by the thorax lift, due to the respiration of about 1 cm and the heartbeat motion at the skin surface in µm to mm scale. The reflected wave is now carrying the information about the driver's vitals consisting of RR, HR and random movement artefacts. Because of the small cardiac body movement, the HR signal comes with a lower SNR-ratio than the RR signal. The incident wave from the surface of the driver's skin is picked up by the same 16-element patch antenna array and gets mixed in the IQ-modulator of the sensor. The analogue I-Q output signal of the radar sensor gets digitized in a 24 Bit ADC of the type ADS1256 at 500 SPS. To receive the phase difference Δφ between the I and Q-channel of the radar sensor, following formula is used:

$$\Delta\varphi(t) = \tan^{-1}\left(\frac{I(t)}{Q(t)}\right) \qquad (1)$$

The phase difference gives an indirect measure of the body movement of the driver. Therefore, the HR and RR can be extracted by DC removal, digital filtering, Fast Fourier transform and peak detection in the time- and frequency domain as shown in Figure 3. To separate the respiration-signal from the heartbeat-signal a digital low-pass filter with a cut-offs frequency at 0.5 Hz is used.

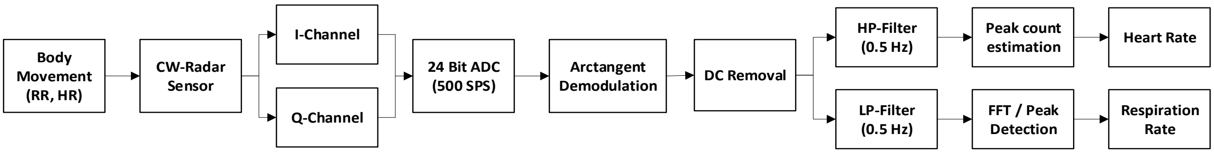

Figure 3: CW-Radar sensor workflow.

3. Results: Radar sensor signal analysis

The radar signal shown in Figure 4 was measured through a cotton T-shirt at the sternum level of the test person at a distance of 5 cm. The large amplitude peaks in the time domain characterize the respiration and the small peaks are associated with the heartbeat of the person. In the frequency domain of the signal two clear peaks at 0.19 Hz and 0.77 Hz show up. The driver's respiration rate (RR) is determined by a maximum peak detection in the frequency-domain of the radar signal. In the power spectrum the peak is located at 0.19 Hz which is equal to a respiration rate of 11.4 breaths per minute. This result is corresponding to the peak count in the time domain with 11 breaths per minute. The second maxima peak in the power spectrum is located at 0.77 Hz/46.2 beats per minute and does not correspond to the correct HR of 54 beats per minute measured with a pulse sensor. Therefore, the HR signal is partly superimposed by the RR signal in the frequency domain.

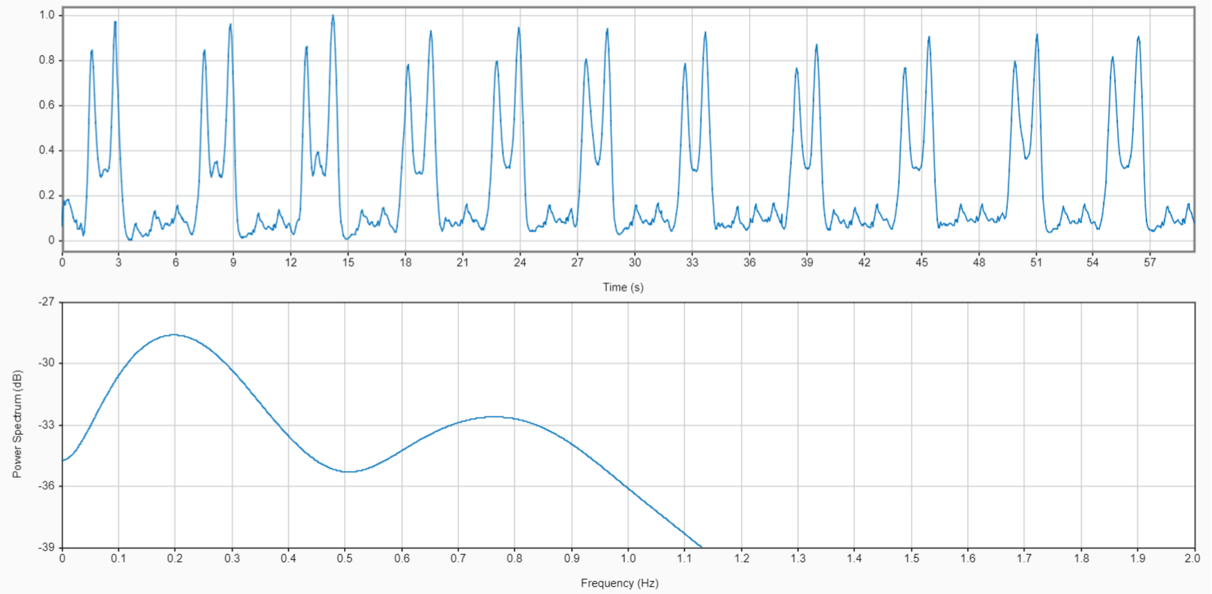

Figure 4: Microwave reflectometer data analysis. Up: Time domain. Down: Frequency domain.

As a solution, a more accurate heart rate (HR) is obtained in the time-domain by a heartbeat count estimation. In this method all local maxima peaks of the high-pass filtered microwave reflectometer data set were considered and giving a more accurate HR of 48 peaks per minute. Compared to the correct HR of 54 beats per minute this method gives better results than maximum peak analysis in the frequency domain.

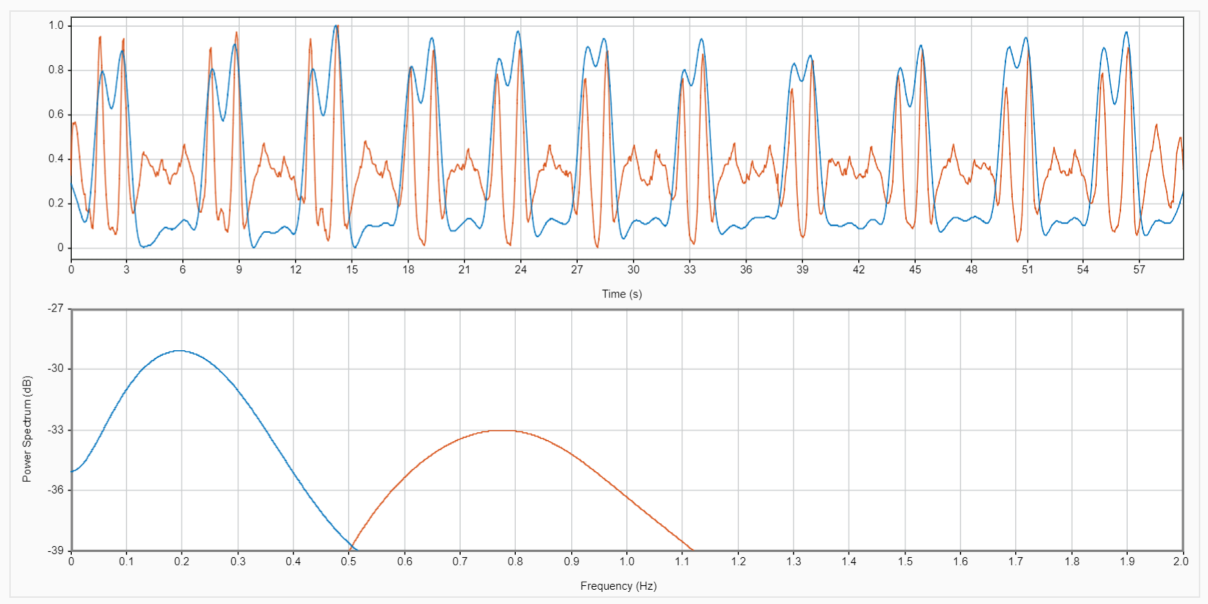

Figure 5: Microwave reflectometer data analysis. Up: Time domain of filtered signals. Down: Frequency domain of filtered signals.

4. Discussion

This paper introduced the innovative concept of a biometric driver seat using a capacitive ECG and radar sensors in construction machine cockpits to increase safety on building sites. The results of the 24 CW-radar sensor data set analysis proves that it is possible to measure the RR of the driver in an accurate and HR of the driver in a sufficiently precise way through a T-shirt and without direct skin contact. We are looking forward, that the concept of this biometric driver seat and the first realisation step by testing its feasibility in our 24 GHz CW-radar sensor study will become a part of modern driver assist and safety systems in future.

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6. References

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