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Radar-assisted health monitoring of primates

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***Abstract* — A feasibility study to detect the respiratory rate and heart rate of primates using non-invasive contactless radar sensors and a dedicated processing pipeline is performed. The proposed approach is validated using measurement data from an individual bonobo, simultaneously collected by two different types of radar sensors (pulsed Ultra Wide Band and FMCW, operating at different frequencies). The results show that it is feasible to infer both respiration and heart rate data from the radar sensors.**

***Keywords* — Non-invasive contactless monitoring of primates, Vital signs monitoring, Radar technology.**

I. Introduction

Respiratory rate (RR) and heart rate (HR) are crucial physiological parameters for monitoring the health conditions of primates in captivity. Conventional contact-based measurement techniques such as respiration belts, electrocardiograms (ECG), and photoplethysmography (PPG) devices would require the primates to be cooperative or necessitate to anaesthetize the animals, which may pose risks to their well-being. Hence, there is a pressing need for accurate and contactless methods to detect and monitor vital signs in primates as part of a wider assessment of their health.

While cameras [1], [2] have been used for contactless vital sign monitoring in humans by measuring changes in skin colour due to alterations in blood volume, they may be less effective for primates due to their denser hair and significant inter-species variations. In this context, radar presents a promising technology for vital signs monitoring [3]–[7], as the method allows for non-invasive and contactless measuring, is not affected by light conditions and less privacy-sensitive than cameras.

For example, Impulse Radio Ultra-Wideband (IR-UWB) radar has been deployed in rescue operations to detect vital signs [8], while Frequency-Modulated Continuous Wave (FMCW) radar has been used in monitoring infants or animal occupants in vehicles [9]. The choice of algorithms for extracting vital signs depends on the radar's operational principles. IR-UWB radar measures range using pulses, with chest motion often inferred from amplitude changes over time, whereas FMCW radar utilizes consecutive chirps to measure distance and velocity, with vital signs estimated from phase information over slow time. In the context of radar for animal monitoring, [10] uses radar to estimate the heart inter-beat interval of chimpanzees, but the study required anesthetization before the measurements. In a further step, the authors in [11] compute different weighted parameters between different simultaneously-operated radars in order to select reliable estimates of vital signs; interestingly, in this study, the animal being monitored, a rhesus monkey, was not anaesthetized at a distance of 6 m from the radar.

In this paper, a processing pipeline is proposed to opportunistically monitor the RR & HR of primates using a single radar system, where 'opportunistically' indicates that the animals are not anaesthetized or influenced by the monitoring process/device. The pipeline incorporates different signal processing steps to extract RR and HR and is validated with measurement data collected with two simultaneously operated radar systems, namely an IR-UWB radar and an FMCW radar. As ground-truth data with a different sensor are difficult to obtain, the simultaneous usage of two diverse radar systems allows us to cross-validate the data. The results of monitoring an individual bonobo measuring through glass from the visitor area side at Apenheul primate park in Apeldoorn, the Netherlands, using the proposed approach, show that it is feasible to infer RR & HR from both radars.

The rest of the article is organized as follows. In Section II, the fundamentals of using radar to monitor RR and HR are provided. The proposed processing pipeline is given in Section III, with test results for monitoring an individual bonobo and discussions in Section III. Finally, conclusions are drawn in Section IV.

II. Fundamentals

A. Signal model of vital signs

The simplest and most common model of vital signs uses two sinusoidal signals with different amplitudes and frequencies to simulate the displacement at the skin surface caused by respiration and heartbeat, respectively. This can be modelled as:

$$x(t) = x_0 + A_r sin(2\pi f_r t) + A_h sin(2\pi f_h t) \tag{1}$$

where x_0 is the initial range of the body skin, A_r & f_r represent the amplitude and frequency of respiration, respectively, and A_h & f_h represent the amplitude and frequency of heartbeat, respectively. The varying time delay τ_d due to the vital signs is then modelled as the sum of the constant time-of-flight τ_0, and two sinusoidal delays associated with respiration and heartbeat:

$$\tau_d(t) = \frac{2x(t)}{c} \tag{2}$$

$x(t)$ is the time-varying distance between the radar and the body part, and c is the speed of light.

B. Radar signal models

IR-UWB radar transmits pulsed waveforms. The time-of-arrival (ToA) of these pulses is denoted by τ_0 and depends on the distance between the radar and subject d_0. The periodically transmitted pulsed signal is decomposed into fast-time domain t' and chirp number domain $l = \lfloor \frac{t}{T} \rfloor$ with $t' = t - lT$, where T is the slow time sampling time. The signal reflected from the subject's body with movement caused by respiration and heartbeat can be written as:

$$y(l,k) = A_I p(lT - \tau_d(kt_s)) \tag{3}$$

where k and l are the sampling indices in fast time and slow time, respectively, t_s is the sampling time in fast time, and A_I is the amplitude of the reflected pulse p.

FMCW radar continuously transmits chirped waveforms, and the echo reflections from objects in the scene are continuously recorded. As for other radar waveforms, the range of the targets will be determined by the waves' round-trip delay, and the characteristics of the CW waveforms must be changed to retrieve the range information (e.g., modulating the wave frequency or phase over time). FMCW can simultaneously estimate ranges and Doppler/velocities at a relatively low sampling frequency with the de-chirping technique. The received signal after de-chirping and sampling in fast time can be written as:

$$z(l,k) = A_F \exp\left[j2\pi\left(\frac{2x(lT)}{\lambda} + \mu\frac{x(lT)}{c}kt_s\right)\right] \tag{4}$$

where A_F is the amplitude of the waveform reflected by the object, and μ is the slope of the chirp. In this signal model, it is assumed that the target movement within the fast time is negligible, a common assumption in FMCW radar processing.

III. Proposed processing pipeline

In a static environment, the resulting clutter for both radar can be considered as a DC-component in the slow-time direction. The clutter does not depend on slow time. Thus, static background clutter can be eliminated first for both radar by filtering methods while maintaining the subject signal. Then the main information on the RR and HR can be extracted from the IR-UWB or FMCW radar data with the proposed pipeline.

For the IR-UWB radar, since the relevant information is already included in the amplitude of the signal, the raw ADC data is directly processed. Due to the short duration of the radar pulse in the time domain, the received signal has a large bandwidth. A bandpass filter with a 3GHz bandwidth starting from 7.25GHz is applied to each row of the raw ADC data collected from the IR-UWB radar. Then, the useful data, i.e., without extra movements from the monitored primate, is extracted for later processing by a time window. A Finite Impulse Response (FIR) filter is used here to clean the signal from its noisy frequency components. Then, a Fast Fourier transform (FFT) over multiple impulse responses is implemented to obtain the frequency peak, which is related to the RR and HR rate.

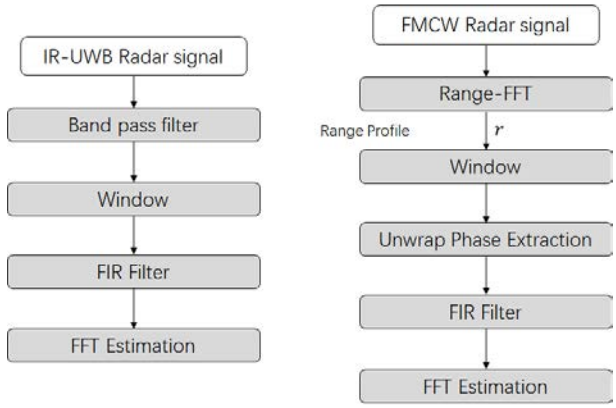


Fig. 1. Proposed processing pipeline for IR-UWB radar and FMCW radar.

FMCW radar contains the RR & HR information in its phase information, as shown in equation (4). The Range-FFT is performed first to detect the range bin corresponding to the monitored primate. Then, in the range-time profile, the useful data is extracted by a time window. Unwrap phase extraction is performed to get the phase information for this range bin over time. The unwrap phase extraction is modelled as follows:

$$\phi(l) = \text{unwrap}\left[tan^{-1}\left(\frac{Q(l)}{I(l)}\right)\right] \tag{5}$$

where the Q and I are the real and imaginary parts of the signal after FFT over the target's range bin.

Similarly to the IR-UWB data, an FIR filter is used, and an FFT is also implemented to estimate the values of the RR and HR.

IV. Test results and discussion

In this section, the test setup for the processing of both IR-UWB and FMCW radar vital signs is described. The radars were placed in different positions but with the monitored primates in their field of view. Testing was done opportunistically through 2 cm glass from the visitor area side at the bonobo inside an enclosure at Apenheul Primate Park (NL). Measurements were taken from an adult female bonobo while she was resting near the glass. All animals could move away freely at all times and were never forced or encouraged to participate. The test setup is shown in Fig. 2. The radar parameters for both radars are provided in Table. 1.

The result of the IR-UWB radar is shown in Fig. 3(a), with a range time plot recorded over 3 minutes. The bonobo is around 1 meter away from the radar. The rectangle marked as '1' denotes the data region chosen for the subsequent processing, whereas the one marked by '2' is chosen for the reference data. Sub-figure (b) is the RR profile for both blocks marked in (a). The peak in the data indicating 14.7 cycles/minutes is the RR recorded for the participant, whereas the power spectrum of the reference data is uniformly distributed in the filter window marked by the blue arrow

Table 1. Radar parameters for the test verification

IR-UWB System Parameters	Value
IR-UWB chipset	Novelda X4
Center Frequency (GHz)	8.7
ADC Sampling Rate (GHz)	23.328
Bandwidth (GHz)	2.95
Slow-time sampling frequency ((Hz))	20
FMCW System Parameters	**Value**
FMCW chipset	TI AWR2243
Center Frequency (GHz)	77
Slope (MHz/us)	30
Sampling Rate (Msps)	6
Bandwidth (GHz)	1.28
PRI (s)	0.115

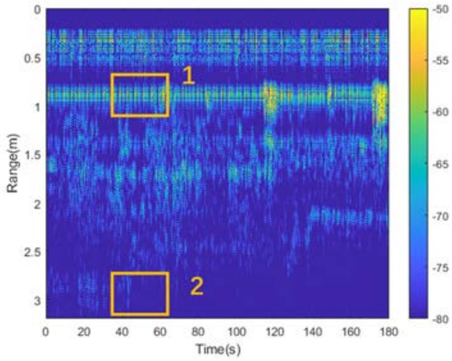
(a) (b)

Fig. 2. Test setup showing the adult female bonobo resting and two radar systems: (a) FMCW radar, (b) IR-UWB radar.

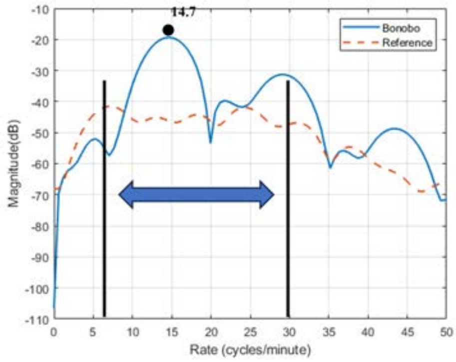
between two solid lines. The magnitude difference between bonobo's data and reference in the frequency domain is larger than 20 dB. The result of a short-time Fourier transform (STFT) of the data in the rectangle marked by '1' is shown in (c). The main frequency component of this spectrogram is also within the 10-20 cycle/minutes. The discontinuity of the rate of 15 cycles/minutes at a time of 110s is partially caused by the bonobo's movement. The final result of HR estimation is shown in Fig. 3 (d). Similar to sub-figure (b), the peak indicates that bonobo's HR is around 72 cycles/min.

The results of the FMCW radar are shown in Fig. 4. (a) shows the range time over 3 minutes, with the bonobo around 2m away from the radar. The bonobo is stably resting during the interval 30-90s, after which the participant starts moving. Rectangle '1' is assumed to be the useful data region, whereas rectangle '2' is the reference data. Sub-figure (b) shows the RR profile for both blocks marked in (a). The peak of the data indicates 17.4 cycles/minutes for RR. (c) shows the result of an STFT on the data in rectangle '1'. The main frequency is also within the 15-20 cycle/minutes. Finally, (d) shows the result of the estimated HR for the participant. Similar to (b), the peak indicates an HR of around 77 cycles/min.

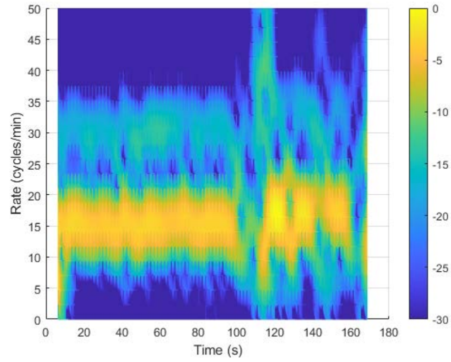
Both independent results of the IR-UWB and FMCW radar provide a similar estimation of bonobo's RR and HR, proving the effectiveness of the proposed processing pipeline. However, the IR-UWB system is expected to be more resilient as a function of the signal-to-noise ratio (SNR), as the signal



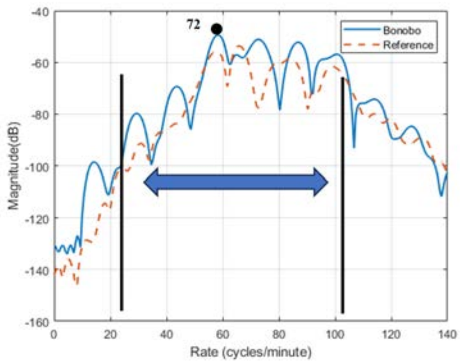
(a)



(b)



(c)



(d)

Fig. 3. Test results from IR-UWB: (a) Range time map, (b) RR estimation, (c) STFT results of RR, (d) HR estimation.

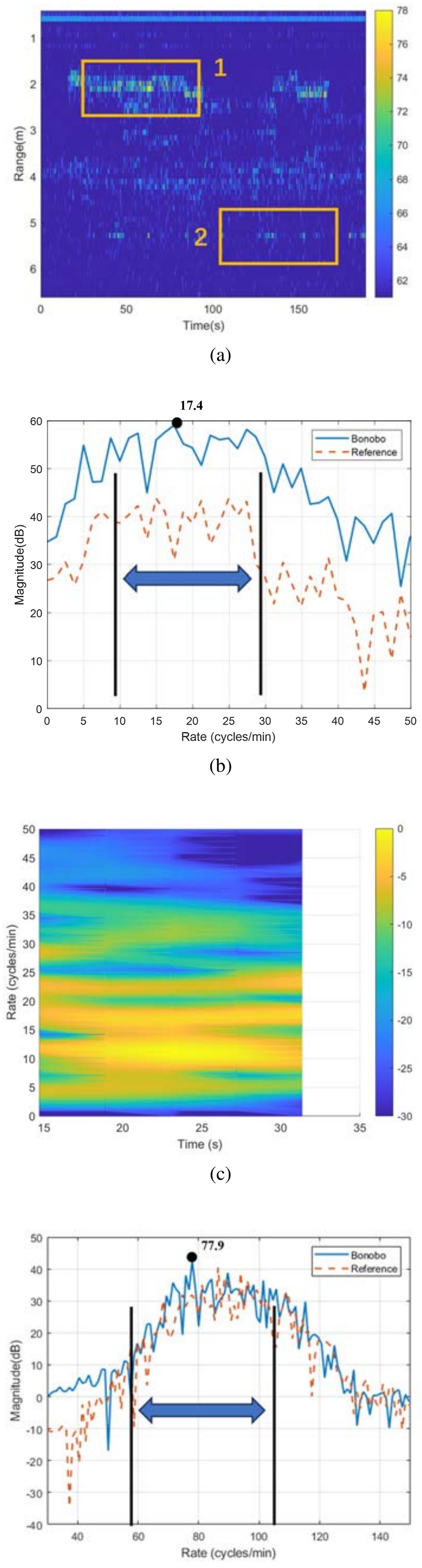


Fig. 4. Test results from FMCW: (a) Range time map, (b) RR estimation (c) STFT results of RR, (d) HR estimation.

magnitude includes the main information for HR and RR directly, while the FMCW uses the phase information, which is more sensitive to the movement and the noise.

V. Conclusion

In this paper, a processing pipeline is proposed to non-invasively monitor RR & HR of non-anaesthetized primates using a single radar. The test data from a bonobo verified the effectiveness of the proposed approach using two independent yet simultaneously operated radar sensors, an IR-UWB and an FMCW radar. While independent ground-truth data with another sensor could not be obtained for practical limitations, the estimated RR & HR data from the both radars showed promising results. Future studies can build on these initial feasibility results to tackle more challenging scenarios with random body movements of the monitored primate and dynamic scenarios with multiple individuals.

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