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INVITED PAPER

Review: Noncontact Sensing of Animals Using Radar

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SUMMARY There has been a growing interest in the application of radar technology to the monitoring of humans and animals and their positions, motions, activities, and vital signs. Radar can be used, for example, to remotely measure vital signs such as respiration and heartbeat without contact. Radar-based human sensing is expected to be adopted in a variety of fields, such as medicine, healthcare, and entertainment, but what can be realized by radar-based animal sensing? This paper reviews the latest research trends in the noncontact sensing of animals using radar systems. We also present examples of our past radar experiments for the respiratory measurement of monkeys and the heartbeat measurement of chimpanzees. The trends in this field are reviewed in terms of the target animal species, type of vital sign, and radar type and selection of frequencies.

key words: *Animals, radar, noncontact sensing, vital signs, body motion*

1. Introduction

The demand for sensing vital signs has increased in a variety of fields, such as medicine, healthcare, security, and entertainment. First, by observing the vital signs and physiological state of a target person, we can assess physical and psychological conditions. Second, by observing vital signs, we can detect signs of diseases and sudden changes in medical conditions and observe chronic diseases in what is expected to be a breakthrough in healthcare and medicine. Although most existing methods of monitoring vital signs are intended to be used for humans, they can be applied to a wide range of non-human animals, which is expected to lead to innovative applications and commercial opportunities [1].

One application of animal sensing is agriculture and livestock farming, where sensors can make livestock production more efficient, sustainable, and precise. A variety of sensors have been studied for the livestock and agriculture industry, and by adopting such sensors, we can obtain information of the animal status (e.g., disease, metabolism, stress, reproduction, behavior, and positioning information) required to improve efficiency and animal welfare [2].

Most conventional sensors, however, require the installation of a device on the body, the clothing, a seat, the bedding, or a mattress. Electrocardiography (ECG), for example, has been established as the standard method for monitoring the heart rate. Implanted ECG radiotelemetry units are widely used as the gold standard for monitoring heart activity, especially for laboratory animals such as mice; such ECG devices have been used in numerous studies on cardiovascular diseases, stress, aging, the circadian rhythm, animal welfare, neurology, toxicology, and cancer [3]. However, wearing such contact-type sensors can create stress for many animals, and in many cases, the use of anesthesia is necessary during installation, which might place the target animals at risk.

It is thus important to introduce a noncontact method for monitoring vital signs, especially for the physiological measurement of non-human animals. One existing noncontact method for monitoring physiological signals involves the use of optical cameras. Its measurement principle is similar to that of photoplethysmography and involves the detection of variations in skin color related to the local blood volume. This method, however, cannot be applied to a body part covered with clothing, hair, or fur. In addition, the accuracy of camera-based sensors deteriorates when the lighting conditions fluctuate.

Recently, new emerging sensing technology using radar has attracted attention. Radar systems can measure vital signs (physiological signals) such as body movements, respiration, the heartbeat, and blood pressure without requiring the troublesome installation of sensors, and measurements can thus be made without making the subject aware of the presence of sensors. The introduction of the noncontact radar sensing of animals can eliminate the stress effects of the repeated handling of animals in taking data as the use of contact-type sensors can be avoided. The use of radar systems avoids such issues because microwaves and millimeter-waves (mmW) penetrate dry clothing, hair, and fur. In addition, the fluctuation of lighting conditions does not

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affect radar measurements.

The volume of data recorded by a radar system is smaller than that recorded by cameras, and radar-based methods are thus suitable for edge computing in embedded systems and reduce the volume of data transmitted in communications [4]. Radar-based methods can therefore be applied in the measurement of humans/animals even if the subjects are dressed or covered with fur in an outdoor setting with fluctuating lighting.

In this paper, we review the latest research trends in the noncontact sensing of animals using radar systems. In Section 2, we first discuss animal species as radar targets in published studies, then discuss the different types of physiological signals of animals that are measured using radar, and finally discuss the radar frequencies used in the radar measurement of animals. In Section 3, we present two examples of our past work on the noncontact sensing of animals using radar systems.

2. Trends in Animal Measurements Using Radar

2.1 Animal Species in Radar Measurement

A variety of animals have been selected as radar targets. Experimental animals are often selected as target animals in radar measurements because of their availability for controlled experiments. Examples of such animals are rats [5]–[13], mice [14], [15], golden hamsters [16], and rabbits [9], [17]–[24].

From the viewpoint of animal welfare, domesticated pets, such as dogs [20], [21], [23], [25]–[32] and cats [21], [23], [26], [31], [33], [34], are often selected for measurement using radar systems. Such application of radar measurement might lead to novel services in the pet industry as the respiration and heartbeat are associated with a pet's physical and psychological stress [35]. In addition, the ability to detect animal vital signs could be applied to emergency protection after disasters, such as finding and distinguishing humans and animals buried under rubble and assessing their survival status [18], [19], [23], [27].

From the viewpoint of improving agricultural efficiency, the measurement of livestock animals, such as broiler chickens [36], cows [4], [37], pigs [31], horses [38], [39], alpacas [38], and mules [38], affects society. The adoption of noncontact measurements for livestock animals is important because the installment and attachment of a sensor can cause psychological stress.

The importance of studying non-human primates lies in the possibility of learning the evolutionary history of humans, and the measurement of physiological signals is important to monitoring the cognitive reactions of non-human primates to experimental conditions. Measurements of non-human primates include the measurements of pig-tailed macaques [40], [41], rhesus monkeys [42], [43], and chimpanzees [44], [45].

The radar-based monitoring of African animals such as giraffes and zebras is important to protecting wildlife from criminal poaching [46]. There are also reports of the radar measurement of bears [47], chameleons [48], [49], bullfrogs [50], tortoises [16], ducks [51], peacocks [34], parakeets [16], and fish [16], [52]–[55]. As discussed so far, radar-based noncontact measurements have been made for many animal species and might lead to innovative services and applications in the future.

2.2 Radar Measurement of Body Movements

There have been many studies on radar measurements related to the time-varying Doppler frequency of the non-translational motion of targets. As for humans and animals, the most dominant component of a micro-Doppler measurement relates to limb movements. Radar-based micro-Doppler measurements can be made to monitor the activity of various animals and to distinguish humans from animals.

Singh et al. [48], for example, measured the body movements of a chameleon using a continuous wave (CW) radar system, and the same group [49] measured the tongue movement of a chameleon using a quasi-millimeter-wave (quasi-mmW) radar system. Bao et al. [31] proposed a method of distinguishing four species (i.e., humans, dogs, cats, pigs) by applying a convolutional neural network to a radar echo spectrogram obtained through time–frequency analysis. Darlis et al. [34] classified humans and animals (i.e., cats and peacocks) using a mmW radar with a convolutional neural network. Schiavoni et al. [38] proposed a method of distinguishing a human from animals (i.e., alpacas, horses, and mules) using ultra-high frequency (UHF) and X-band radar systems. Van Eeden et al. [46] proposed a method of distinguishing between humans and African animals (e.g., giraffes and zebras) using an X-band frequency-modulated continuous-wave (FMCW) radar system.

There have also been studies on the radar-based classification of stationary humans and animals, where the target humans and animals have little to no limb motion. In this case, most of the information contained in the micro-Doppler components comes from the respiratory pattern. Ma et al. [56], for example, proposed a method of distinguishing a stationary human and dog using a ultrawideband (UWB) radar system with a central frequency of 500 MHz in a through-the-wall experimental setup. Ma et al. [23] proposed a method of distinguishing stationary humans, dogs, cats, and rabbits through respiration in a through-the-wall setting using a UWB radar system with a central frequency of 500 MHz and a multiscale residual attention network.

2.3 Radar Measurement of Respiration

The measurement of respiration is important in detecting the early signs of physical and psychological stress, respiratory infections. The displacement due to respiration is greater than that due to the heartbeat, and it is thus easier to measure respiratory activities although the difficulty depends on the species. Humans typically have a respiratory rate of 16.6 ± 2.8 breaths per minute, a respiratory cycle of 3.6 ± 0.5 s, an inspiratory time shorter than the expiratory time by 1.6 ± 0.3 s, and a tidal volume of 383 ± 91 mL per minute. The displacement due to respiration is affected by both thoracic and abdominal movements.

Changes in the cross-sectional radius of the thorax at the third (around the thoracic) and seventh (around the abdominal) costae due to these movements have been reported to be approximately 10.7 and 14.0 mm, respectively. Among the thoracic costae, the greatest displacement occurs near the sternum, and it has been reported that the sternal area is displaced forward by approximately 4.3 mm during inspiration, whereas the abdominal area is also displaced forward, by approximately 4.0 mm, during inspiration [57]. In general, the peak-to-peak displacement of the chest in the normal breathing of adults is between 4 and 12 mm [58], [59].

Lin [17] measured the respiration of a rabbit using a CW radar. Suzuki et al. [47] measured the respiration of a hibernating black bear using a CW radar. Ma et al. [20] measured the respiration of a rabbit tied up and deprived of water and food using UWB radar with a central frequency of 7.3 GHz and a bandwidth of 2.5 GHz. Wang et al. [26] measured the respiration (gill breathing) of a fish (grouper) using an FMCW radar system. Zhao et al. [29] proposed a method of distinguishing a human from a dog using their respiratory features in a post-disaster trapped scenario using a UWB radar with a central frequency of 500 MHz and a bandwidth of 500 MHz. Tuan et al. [4] measured the respiration of a cow using a mmW FMCW radar system. Matsumoto et al. [39] measured the respiration of a horse using an FMCW radar system. Yu et al. [24] measured the heartbeat of anesthetized rabbits in hemorrhage states using a quasi-mmW radar system.

2.4 Radar Measurement of the Heartbeat

The displacement due to a heartbeat is smaller than that due to respiration and difficult to measure in a noncontact manner using a radar system. Regarding the heartbeats of humans, the body displacement was reported to have a peak-to-peak value of 0.5 mm [60], although the cited study measured the displacement surface directly above the heart, and this area is known to have the largest skin displacement due to heartbeats and pulse waves among body regions. Displacements are generally smaller at other sites.

Wang et al. [21] measured the heartbeats and respiration of dogs, cats, rabbits, and humans using impulse radio ultrawideband (IR-UWB) radar with a central frequency of 7.29 GHz and a bandwidth of 1.4 GHz. Matsui et al. [18] measured the heartbeat and respiration of a rabbit using a 1.2-GHz microwave radar system. Churkin and Anishchenko [9] measured both the heartbeats and respiration of a sleeping rat and rabbit using a 100-GHz radar system. Juan et al. [13] used a self-injection-locked (SIL) radar system to measure the respiration and heartbeat of a mouse. Wang et al. [26] measured both the heartbeats and respiration of a sleeping dog and cat using a UWB radar with a frequency band between 6.0 and 8.5 GHz. Hossain et al. [36] used quasi-mmW CW radar to measure the heartbeats of broiler chickens and evaluated the accuracy of the measurement by comparing with ECG data.

2.5 Radar Frequency in Animal Measurements

Radar-based physiological sensing depends on the phase change over time due to displacement. The use of a higher radar frequency is advantageous if a small displacement is to be detected, whereas if the displacement is sufficiently large relative to the wavelength, a low radar freuqncy can also be used. The use of low-frequency microwaves has the advantage that low-cost systems can be adopted, although the antennas and circuits are generally large and it is difficult to make the overall system compact and portable. Radar systems with a variety of frequency bands have been reviewed [37].

We first review studies that made radar measurements of animals in the UHF (300 MHz–3 GHz) band but not in the microwave (> 1 GHz) band. Yu et al. [25] used the UHF band of 400 MHz for radar measurement; Ma et al. [20], Zhao et al. [29], Hafner et al. [52], and Yin et al. [22] used the UHF band of 500 MHz for radar measurement; Schiavoni et al. [38] used UHF radar; and Hui et al. [16] used a 950-MHz transmitting signal that passed through passive harmonic RFID tags to monitor the respiration and heartbeat of small animals (i.e., a golden hamster, parakeet, Russian tortoise, and betta splendens).

We next review studies that used microwave radar systems in the L band (1–2 GHz) and S band (2–4 GHz). Matsui et al. [18], [19] used 1.2-GHz low-frequency microwaves; Bao et al. [31] used 1–2-GHz microwaves. In addition, the low-frequency microwave band at 2.4 GHz is often used as it corresponds to the industrial, scientific, and medical band that can be used without a government license. Hafner et al. [53], [54], Juan et al. [13], and Gordon et al. [14] all used the 2.4-GHz band. Among studies that used microwave radar systems in the C band (4–8 GHz), Zeng et al. [5] used 5.8-GHz microwaves and Ma et al. [20], [27] and Wang et al. [21], [28] used 7.3-GHz microwaves.

We next review studies that used X-band (8–12 GHz) radar systems. Schiavoni et al. [38] and Gong et al. [51] used an X-band radar but did not mention the actual frequencies. Singh et al. [48], van Eeden et al. [46], Lin [17], Suzuki et al. [47], and Kropveld et al. [15] all used 10-GHz radar systems.

Gong et al. [51] used the Ku band (12–18 GHz) but did not mention the actual frequency. Anishchenko et al. [7] used a 13.8-GHz radar system. The K band of microwaves (18–26.5 GHz) is also referred to as the quasi-mmW band. Yu et al. [24], Hossain et al. [36], Singh et al. [49], Lai et al. [33], and Tazen et al. [32] all used 24-GHz radar systems for animal measurements.

Recently, mmW (30–300 GHz) radar systems have been widely used because they are available at a low cost and have high sensitivity to small displacements, which makes the mmW radar an attractive option for the physiological measurement of humans and animals. Huang et al. [10]–[12] used a 60-GHz radar system; Darlis et al. [34] and Wang et al. [26], [55] used 77-GHz radar systems; and Tuan et al. [4], Matsumoto et al. [39], [45], Iwata et al. [44], and Sakamoto et al. [42] used 79-GHz radar systems. An even higher frequency of 100 GHz was used by Churkin and Anishchenko [9] and Ma et al. [50] for radar measurements of rats and rabbits.

2.6 Distance between Animals and Radar Antennas

As the accuracy of the radar-based measurement of physiological signals depends on the signal-to-noise ratio (SNR), it is important to set up a measurement system that ensures a high signal power of echoes reflected off the target animals, although the accuracy also depends on the interference of multiple echoes, large body movements [42], and the physiological nature of the target humans/animals. In addition, a low SNR can be acceptable in measuring body movements, whereas a high SNR is required to measure the heartbeat. Therefore, one selects an appropriate distance to the target animal according to the target animal species and target physiological signals.

The radar equation shows that the echo power P_{r} is proportional to σ and $1/r^4$, where σ is the radar cross section and $r(\simeq d_0)$ is the distance between the target animal and radar antenna (i.e., $P_{\mathrm{r}} \propto \sigma/r^4$). In general, to measure the physiological signals of small animals (small σ), the distance r must be short to ensure a large echo power.

For small animals such as rats, radar antennas are placed close to the target animal in general. Hafner et al. [53], [54], for example, installed a radar antenna directly on a target fish (i.e., $r = 0$); Lai et al. [33] set $r = 0$ and $r = 0.1$ m for a cat; Hossain et al. [36] set $r = 0.2$ m for a broiler chicken; Huan et al. [10], [12] and Anishchenko et al. [6] both set $r = 0.3$ m for a rat; Lin [17] and Yu et al. [24] both set $r = 0.3$ m for a rabbit; Tazen et al. [32] set $r = 0.3$ m for a dog; Matsui et al. [18], [19] set $r = 0.4$ m for a rabbit; Wang et al. [55] set $r = 0.4$ m for a fish; and Juan et al. [13] set $r = 0.5$ m for a rat in a box.

For larger animals, the radar antennas can be placed farther from the target animals. Ma et al. [20], for example, set $r = 0.6$ m for a dog; Ma et al. [20] set $r = 0.6$ m for a rabbit; Ma et al. [50] set $r = 0.6$ m for a bullfrog; Zeng et al. [5] set $r = 0.7$ m for a rat; and Iwata et al. [44] and Matsumoto et al. [45] set $r = 0.7$ m for a chimpanzee. Among studies adopting $r \geq 1$ m, Ma et al. [27] and Wang et al. [21], [28] set $r = 1.0$ m for a dog; Matsumoto et al. [39] set $r = 1.5$ m for a horse; Hui et al. [16] set $r = 1.5$ m for a golden hamster, parakeet, Russian tortoise, and betta splendens; and Darlis et al. [34] set $r = 0.5$, 1.0, and 2.0 m for a cat and peacock.

Among studies adopting a larger distance $r > 2$ m, Bao et al. [31] set $r = 2.5$ m for a dog, cat, and pig; Ma et al. [23] set $r = 2.5$ m for a dog, cat, and rabbit; Yu et al. [25] set $r = 3$ m for a dog; Yin et al. [22] set $r = 3$ m for a rabbit; Minami et al. [43] and Sakamoto et al. [42] set $r > 5$ m for a rhesus macaque; Gong et al. [51] set $r = 11.8$ m for birds; and van Eeden et al. [46] set $r = 1$–3 km for African wild animals. As discussed in this subsection, the distance between the radar antenna and target animal is selected to be less than 3 m in many cases, especially for the measurement of tiny displacements of small animals. Studies on the radar measurements of animals are summarized in Table 1.

3. Examples of Radar-based Measurements of Animals

3.1 Respiratory Measurement of a Rhesus Macaque

In our study [42], we developed an accurate method for the noncontact respiratory measurement of a rhesus monkey using a mmW radar system. Relatively large and gentle animals, such as horses and cows, do not make frequent body movements, and conventional radar-based sensing techniques can thus be used for their respiratory measurement. In contrast, the radar measurement of smaller animals that make frequent movements is much more difficult and its accuracy is reduced by the body motion components contained in the radar signals.

As rhesus monkeys are generally restless and hyperactive by nature, the study [42] developed a method of suppressing their body motion components in radar signals and accurately estimated the respiratory intervals. Our method suppresses nonperiodic components due to body movements and emphasizes periodic components due to respiration contained in the radar echoes. The method combines information from multiple echoes to improve the accuracy of respiratory

Table 1: Classification of Studies on the Radar-based Measurement of Animals

Species	Signal Type, Radar Type, and Frequency		
Rats, Mice	[14]$^{\mathrm{R}}$ (2.4 GHz, RF energy changes, 1983)	[15]$^{\mathrm{M}}$ (10 GHz, Doppler, 1993)	[5]$^{\mathrm{R}}$ (5.8 GHz, Pulse, 2011)
	[6]$^{\mathrm{M}}$ (-, -, 2014)	[7]$^{\mathrm{R}}$ (14 GHz, CW, 2015)	[9]$^{\mathrm{RH}}$ (100 GHz, CW, 2015)
	[10]$^{\mathrm{RH}}$ (60 GHz, CW, 2015)	[8]$^{\mathrm{R}}$ (3.8 GHz and 14 GHz, SFCW, 2015)	[11]$^{\mathrm{H}}$ (60 GHz, CW, 2016)
	[12]$^{\mathrm{RH}}$ (60 GHz, CW, 2017)	[13]$^{\mathrm{RH}}$ (2.4 GHz, SIL, 2019)	[16]$^{\mathrm{RH*}}$(950 MHz, FMCW, 2019)
Rabbits	[17]$^{\mathrm{R}}$ (10 GHz, RF energy changes, 1975)	[18]$^{\mathrm{RH}}$ (1.2 GHz, Doppler, 2004)	[19]$^{\mathrm{RH}}$ (1.2 GHz, Doppler, 2004)
	[9]$^{\mathrm{RH}}$ (100 GHz, CW, 2015)	[21]$^{\mathrm{RH}}$ (8 GHz, IR-UWB, 2019)	[20]$^{\mathrm{R}}$ (7.3 GHz, IR-UWB, 2019)
	[21]$^{\mathrm{RH}}$ (7.3 GHz, IR-UWB, 2019)	[22]$^{\mathrm{M}}$ (500 MHz, UWB, 2019)	[23]$^{\mathrm{RM}}$ (500 MHz, UWB, 2020)
	[24]$^{\mathrm{R}}$ (24 GHz, CW, 2021)		
Dogs	[25]$^{\mathrm{M}}$ (400 MHz, UWB, 2016)	[21]$^{\mathrm{RH}}$ (8 GHz , IR-UWB, 2019)	[56]$^{\mathrm{M}}$ (500 MHz, UWB, 2019)
	[28]$^{\mathrm{RH}}$ (7.3 GHz, IR-UWB, 2019)	[26]$^{\mathrm{RH}}$ (7.3 GHz, UWB, 2020)	[23]$^{\mathrm{RM}}$ (500 MHz, UWB, 2020)
	[29]$^{\mathrm{M}}$ (500 MHz, UWB, 2021)	[27]$^{\mathrm{HM}}$ (7.3 GHz, UWB, 2021)	[32]$^{\mathrm{H}}$ (24 GHz, CW, 2023)
	[34]$^{\mathrm{M}}$ (1.5 GHz, UWB, 2023)	[30]$^{\mathrm{H}}$ (No Data, IR-UWB, 2023)	
Cats	[21]$^{\mathrm{RH}}$ (8 GHz , IR-UWB, 2019)	[23]$^{\mathrm{RM}}$ (500 MHz, UWB, 2020)	[26]$^{\mathrm{RH}}$ (7.3 GHz, UWB, 2020)
	[33]$^{\mathrm{RH}}$ (24 GHz, CW, 2022)	[31]$^{\mathrm{M}}$ (1.5 GHz, UWB, 2023)	[34]$^{\mathrm{M}}$ (77 GHz, FMCW, 2023)
Cows	[37]$^{\mathrm{RH}}$ (2.4 GHz, SIL, 2017)	[4]$^{\mathrm{R}}$ (79 GHz, FMCW, 2022)	
Pigs	[31]* (1.5 GHz, UWB, 2023)		
Horses	[38]$^{\mathrm{M}}$ (UHF, Doppler, 2014)	[39]$^{\mathrm{R}}$ (79 GHz, FMCW, 2022)	
Mules	[38]$^{\mathrm{M}}$ (UHF, Doppler, 2014)		
Zebras	[46]$^{\mathrm{M}}$ (X-band, FMCW, 2018)		
Giraffes	[46]$^{\mathrm{M}}$ (X-band, FMCW, 2018)		
Alpacas	[38]$^{\mathrm{M}}$ (UHF, Doppler, 2014)		
Bears	[47]$^{\mathrm{RH}}$ (10 GHz, Doppler, 2009)		
Monkeys	[41]$^{\mathrm{R}}$ (10 GHz, CW, 1979)	[40]$^{\mathrm{R}}$ (10 GHz, CW, 1979)	[42]$^{\mathrm{R}}$ (79 GHz, FMCW, 2023)
	[43]$^{\mathrm{HP}}$ (79 GHz, FMCW, 2023)		
Chimpanzees	[44]$^{\mathrm{H}}$ (79 GHz, FMCW, 2023)	[45]$^{\mathrm{HP}}$ (79 GHz, FMCW, 2023)	
Birds	[16]$^{\mathrm{RH}}$ (950 MHz, FMCW, 2019)	[51]$^{\mathrm{R}}$ (S, X, and Ku-band, DS, 2022)	[34]$^{\mathrm{M}}$ (77 GHz, FMCW, 2023)
	[36]$^{\mathrm{R}}$ (24 GHz, CW, 2023)		
Lizards	[48]$^{\mathrm{M}}$ (24 GHz, CW, 2012)	[49]$^{\mathrm{M}}$ (11 GHz, CW, 2012)	
Tortoises	[16]$^{\mathrm{RH}}$ (950 MHz, FMCW, 2019)		
Frogs	[50]$^{\mathrm{R}}$ (100 GHz, CW, 2019)		
Fish	[52]$^{\mathrm{M}}$ (500 MHz, Doppler, 2008)	[53]$^{\mathrm{H**}}$(2.4 GHz, CW, 2010)	[54]$^{\mathrm{H**}}$(2.4 GHz, CW, 2013)
	[16]$^{\mathrm{RH}}$ (950 MHz, FMCW, 2019)	[55]$^{\mathrm{R}}$ (77 GHz, FMCW, 2022)	

$^{\mathrm{R}}$: Respiration measurement.

$^{\mathrm{H}}$: Heartbeat measurement.

$^{\mathrm{M}}$: Body motion measurement and classification.

* : Hamster.

** : Antenna is directly attached to the target body.

$^{\mathrm{P}}$: Preprints without peer review.

measurement by emphasizing the periodic components related to respiration, whereas in many conventional methods, the respiratory interval is estimated from the signal for a specific point corresponding to the maximum peak in the radar image.

We used a pair of mmW array radar systems and evaluated the measurement accuracy by comparing estimates obtained with the two systems as attaching contact-type respiration sensors to a rhesus monkey is not easy. Both were 79-GHz FMCW radar systems with a multiple-input and multiple-output array having a bandwidth of 3.6 GHz. The beamwidths in the E-plane of the transmitting and receiving elements were ±4° and ±4° respectively whereas the beamwidths in the H-plane of the transmitting and receiving elements were ±33° and ±45°, respectively. The multiple-input and multiple-output array comprised three transmitting and four receiving elements, with the spacings between transmitting elements begin 7.6 mm (2λ) and the spacings between receiving elements being 1.9 mm ($\lambda/2$).

Our experiments were conducted at a cylindrical monkey enclosure at the Kyoto City Zoo, where 12 rhesus monkeys were housed. The diameter and depth of the enclosure were 18.0 and 4.0 m, respectively, as shown in Figs. 1 and 2. Using the developed method, the respiratory intervals of a monkey were measured as shown in Fig. 3. Estimations are missing for the period 75 s $\leq t \leq$ 80 s owing to the body movements of the target monkey. The root-mean-square difference (error) between the estimated respiratory intervals obtained with radar systems 1 and 2 was 0.08 s, which is sufficiently small relative to the average respiratory interval, demonstrating the effectiveness of the developed method.

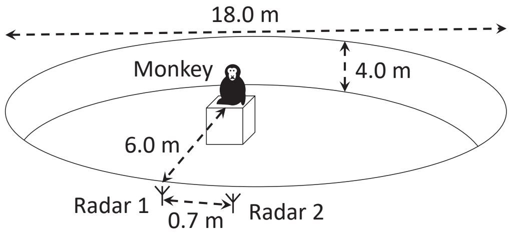

Fig. 1: Schematic of the experiment using a pair of radar systems on a rhesus monkey [42].

Fig. 2: Photograph of the experimental site in the zoo [42].

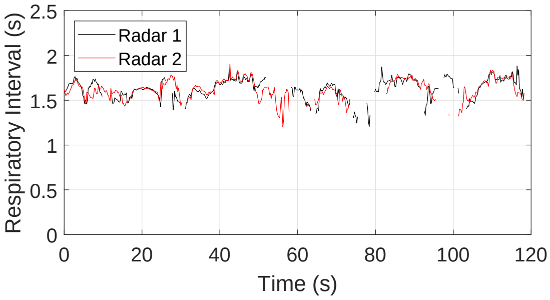

Fig. 3: Respiratory intervals estimated from radar systems 1 (black) and 2 (red) [42].

3.2 Measurement of the Heartbeat of a Chimpanzee

In our study [44], we measured the heart interbeat interval (IBI) of a chimpanzee using a mmW radar system. In measuring a heartbeat using a radar system, the most challenging task is to suppress the effect of the respiration because the displacement due to the heartbeat is much smaller than that due to the respiration. The fundamental frequency of the heartbeat is known to be in the range of 1.0–1.7 Hz for humans and 1.5–2.2 Hz for chimpanzees, which can be masked by higher harmonic frequency of the respiration.

The study provided a method of optimizing the cutoff frequency of a high-pass filter to suppress the respiratory component contained in the radar signal. To determine the cutoff frequency, our approach is to suppress the fundamental frequency component of the heartbeat while maintaining the second harmonic frequency. In adopting the method, we identify the second harmonic frequency of the heartbeat using the power spectrum of the body displacement and set the optimum cutoff frequency to extract the second harmonic frequency of the heartbeat.

We used the same FMCW radar system described in the previous subsection for the respiratory measurement of the rhesus monkey. The measurement was performed during a health checkup of the chimpanzee (adult male), who was anesthetized before the experiment. The distance between the radar antenna and the chimpanzee was 0.7 m and the radar module faced the front chest wall. During the measurement, ECG electrodes were attached to the chimpanzee's arm and leg.

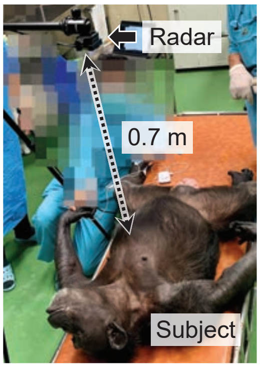

Fig. 4: Photograph of the subject chimpanzee during the radar measurement [44].

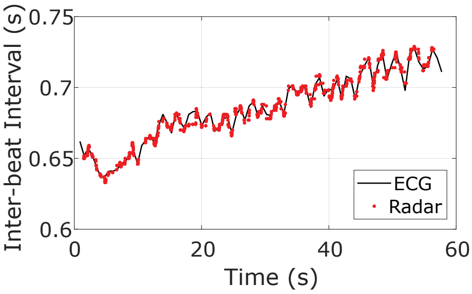

Fig. 5: IBIs estimated using radar (red dots) and ECG (black line) for the chimpanzee [44].

The IBI estimated using the proposed method is shown in Fig. 5. The figure shows good agreement between the IBIs obtained from the radar and ECG. In addition, it is seen that the IBI increases with time, possibly because the chimpanzee calmed down during the experiment. The root-mean-square error of the IBI estimation was 2.6 ms, which is sufficiently small relative to the average IBI. This result suggests the effectiveness of our method in making a noncontact heartbeat measurement of a chimpanzee using a radar system.

4. Conclusion

In this paper, we surveyed and reviewed recent studies on radar-based measurements of animals. We first reviewed animal species that have been measured using radar systems in published studies. Numerous studies involved rats, mice, rabbits, dogs and cats. There were also studies involving cows, horses, birds, fish, monkeys and chimpanzees. We then discussed the types of physiological signals and their applications. The measurements of body movements were often used for the identification of humans and animals. In addition, there were numerous studies on the measurements of respiration and heartbeats. We then discussed the selection of frequency in radar-based animal measurements. Although the phase shift due to the displacement is proportional to the frequency and higher frequencies are sensitive to small motion, researchers have introduced a variety of radar systems with different frequency bands for animal sensing. This variety is partly due to system costs and partly due to the accuracy being dependent on other factors, such as the interference of echoes, large body movements, and the physiological nature of the target subject. Finally, we gave two examples of the radar-based measurement of animals. One example was the respiratory measurement of a rhesus monkey and the other was the heartbeat measurement of a chimpanzee. We believe that this review paper will benefit researchers who are interested in the measurement of animals using radar systems.

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Ethics Declarations

The experimental protocols involving chimpanzees were approved by the Animal Experimentation Committee of the Wildlife Research Center, Kyoto University (WRC-2022-KS002A), and the experimental protocols involving rhesus monkeys was approved by the Research Ethics Committee of the Kyoto City Zoo (approval number: 2022-KCZ-006).

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