A Review on Recent Progress of Portable Short-Range Noncontact Microwave Radar Systems

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Abstract:
This paper reviews recent progress of portable short-range noncontact microwave radar systems for motion detection, positioning, and imaging applications. With the continuous advancements of modern semiconductor technologies and embedded computing, many functionalities that could only be achieved by bulky radar systems in the past are now integrated into portable devices with integrated circuit chips and printed circuits boards. These portable solutions are able to provide high motion detection sensitivity, excellent signal-to-noise ratio, and satisfactory range detection capability. Assisted by on-board signal processing algorithms, they can play important roles in various areas, such as health and elderly care, veterinary monitoring, human-computer interaction, structural monitoring, indoor tracking, and wind engineering. This paper reviews some system architectures and practical implementations for typical wireless sensing applications. It also discusses potential future developments for the next-generation portable smart radar systems.

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SECTION I. Introduction

Portable short-range noncontact microwave radar systems with embedded control and communication links have the potential to improve the quality of service in a plurality of areas, such as healthcare, agriculture, infrastructure maintenance, and energy conservation.

By monitoring small mechanical motion and displacement, short-range microwave radars have been investigated for human and animal vital signs detection for a few decades [1]–[2][3][4][4][5][6][7][8][9][10]. Benefiting from the rapid developments of semiconductor technologies, significant advancements in hardware miniaturization and human and animal studies have taken place since the beginning of this century. With focused radiation beams, the technology is further developed into auditory radars for vocal signal detection in applications such as noise rejection, directional discrimination, and remote voice recording [11]–[12][13][14]. In cancer radiotherapy, accurate noncontact respiratory monitoring provides a method to dynamically target a tumor with a radiation beam even when the tumor moves due to the respiratory movement of a patient [15]–[16][17]. On the other hand, being able to sense the mechanical vibration and deflection of building structures enables smart microwave radar sensors for structural health monitoring (SHM) to address worldwide concerns on aging infrastructures [18], [19].

Not limited to the detection of motion waveforms, a time–frequency analysis provides a dynamic way for short-range radars to interpret motion patterns [20], [21], based on which applications including gait analysis, fall detection, gesture characterization, and occupancy sensing have emerged in military and civilian scenarios [22], [23]. In addition, time–frequency analysis of short-range radar signals provides an excellent way to interrogate in real-time the status of rotating structures, which has stimulated the research and application of microwave radar sensors for online monitoring of wind turbine blades [24]–[25][26][27]. Technical challenges and solutions in these areas will be discussed.

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Another growing area for short-range microwave/millimeter wave radar is precise localization and tracking by measuring distance and angle of arrival [28]–[29][30]. By transmitting over a bandwidth, frequency-modulated continuous-wave (FMCW) radars and ultrawideband (UWB) radars can accurately localize targets and track their displacements even in a complex indoor environment [31], [32]. Recent advancements for positioning assisted by advanced beamforming and inverse synthetic aperture radar (ISAR) have demonstrated important indoor applications. On the other hand, some innovative multiple-input single-output and multiple-input multiple-output solutions that track moving objects using a few discrete radio frequencies may enhance access to the limited radio spectrum [33]. Although conventional tracking and localization radar sensors were mostly made of large equipment, advanced SiGe/GaN/CMOS technologies, and system methods, such as those exploiting injection locking and six-port architectures, enabled the minimization of tracking and localization radars and significantly broadened their operation frequency range [34], [35].

This paper provides an overview of the recent progress on the development of smart microwave radar systems aided with advanced technologies, such as injection locking, ISAR, flexible electronics, and software-configurable circuits. The scope of applications extends to sleep study, veterinary monitoring and animal study, fall detection, indoor localization, smart house, tumor tracking during cancer treatment, and structure monitoring for civil and wind energy infrastructures. While there are abundant developments on UWB pulsed radar in recent years [36]–[37][38][39][40], this review will be focused on portable continuous-wave (CW) radar systems. It should also be noted that this paper is focused on emerging applications in areas such as biomedical, animal, mechanical, and structural monitoring. While there are many advanced research and applications of 24-GHz and millimeter-wave automotive radar systems, they involve many techniques that are different from the ones reviewed in this paper, and thus are out of scope of this paper. Interested readers are encouraged to refer to [41]–[42][43][44][45][46][47].

This paper starts with the fundamental theory of CW radar, including interferometry radar, FMCW radar, and hybrid mode radar in Section II. It then presents application-oriented case studies of motion and displacement monitoring systems in Section III, which also addresses usage of time–frequency analysis for motion sensing systems. Section IV discusses systems with localization and tracking capabilities. Finally, the outlook for portable short-range microwave radar sensing systems will be discussed in Section V.

SECTION II.
Fundamental Theory of Continuous-Wave Radar

In a basic CW radar system, a known stable-frequency CW radio signal is transmitted, reflected by objects on the radio signal path, and captured by a receiver in the radar system. CW radars can operate in various modes, either unmodulated or modulated. Among them, perhaps the most frequently used ones are the Doppler mode and the FMCW mode.

A. Doppler and Interferometry Radar Systems

Typically, a Doppler radar sends out a single-tone radio signal with frequency f_t . Upon hitting an object, the associated return-signal frequency is shifted away from the transmitted frequency based on the Doppler effect when the object is moving. The backscattered signal frequency f_r received by the radar depends on the speed of light c in the air and the speed v of the target: $f_r = f_t (1 + v/c)/(1 - v/c)$. The Doppler frequency shift is thus $f_d = f_r - f_t = 2vf_t/(c - v)$. Doppler radars are typically used to remotely determine the speed of moving vehicles and to monitor the speed in competition sports, such as golf, tennis, baseball, and NASCAR racing. Because there is no modulation involved and the transmitted signal has a single tone, Doppler radars can be realized at a very low cost.

Because signal frequency and phase are related to each other, a similar architecture operating at a single frequency can be used as an interferometry radar to detect the phase change between the transmitted (TX) and received (RX) signals. Interferometry is an important measurement technique in a large variety of fields, such as astronomy, fiber optics, engineering metrology, optical metrology, seismology, spectroscopy, quantum mechanics, remote sensing, biomolecular interactions, surface profiling, microfluidics, mechanical stress/strain measurement and velocimetry, small-displacement measurement, and detection of refractive index changes and surface irregularities [48]. Fig. 1 shows the mechanism for interferometry-radar operation in displacement measurement. The transmitted and received signals have the same frequency, but they have a phase delay $\Delta\phi$ due to the signal propagation path. Without considering the noise and delay associated with the electronic circuitry, $\Delta\phi$ will be proportional to the displacement that is less than $\lambda/2$, where λ is the wavelength. By detecting the change in $\Delta\phi$, the displacement of the target will be determined. The radar receiver uses the same transmitted signal as the local oscillator signal for the down-converter, so that it attains coherent detection with very high displacement detection accuracy. For example, a 2.4-GHz carrier frequency could achieve millimeter-scale displacement measurement accuracy [49].

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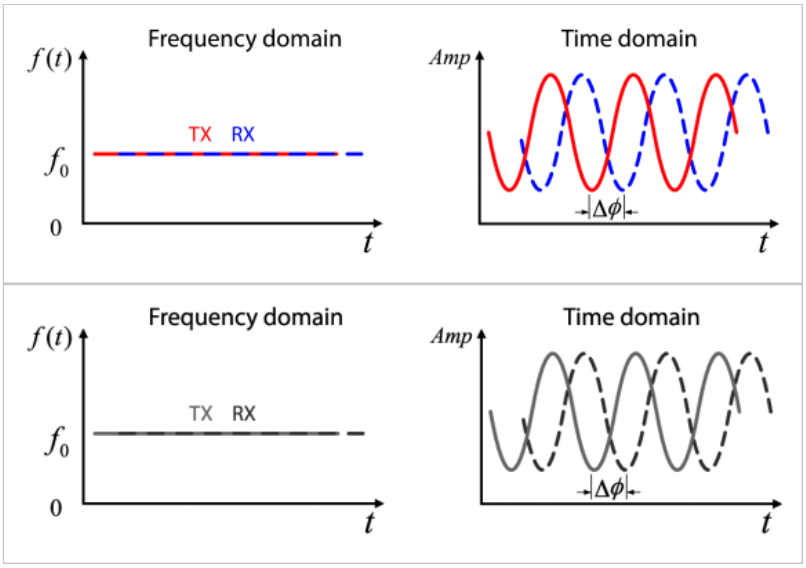
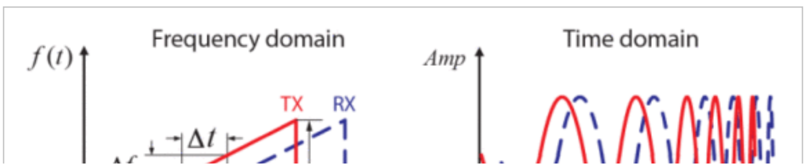


Fig. 1.
Interferometry operation for displacement monitoring.

Doppler and interferometry radars have advantages of simple architecture, narrowband operation, low cost, and can achieve highly accurate speed and displacement measurement. However, they cannot measure absolute distance (i.e., range) of a target.

B. Frequency-Modulated Continuous-Wave Systems

FMCW radars are capable of determining the absolute distance between the system and a target. A variety of modulations for the transmitted signal is possible with the transmitter frequency being able to slew up and down as sine wave, sawtooth wave, triangle wave, or square wave. The basic operation is illustrated in Fig. 2, in which the sawtooth frequency modulation is considered as an example. In this system, the received waveform (RX) is simply a delayed replica of the transmitted waveform (TX). A local copy of the transmitted signal is used to down-convert the received signal to baseband, and the amount of frequency shift Δf between the transmit signal and the reflected signal (i.e., the beat frequency f_b) is linearly proportional to the time delay Δt , leading to $f_b = \Delta t \cdot B/T$, where B is the modulation bandwidth and T is the frequency-modulation sweep time. The range can be thus obtained as $R = c \cdot f_b \cdot T/(2B)$. With the advent of modern electronics, the baseband signal is typically passed through an analog-to-digital converter, and digital processing is performed on the result. The range resolution ΔR of an FMCW radar refers to the minimum separation (in range) of two targets of equal cross section that can be resolved as separate targets, and was found to be proportional to $c/(2B)$. This means that a large modulation bandwidth is needed to achieve a high range resolution. It is worth noting that FMCW radars can extract Doppler information related to the target's velocity, and thus measure displacements of targets if the coherence property of the system is achieved. For example, Wang *et al.* [50] demonstrated tracking of mm-scale human chest wall movements using a linear FMCW radar with a 160-MHz instantaneous transmitted bandwidth centered at 5.8 GHz. However, the hardware and signal processing for an FMCW system to measure displacements are more complex than those of unmodulated CW systems.



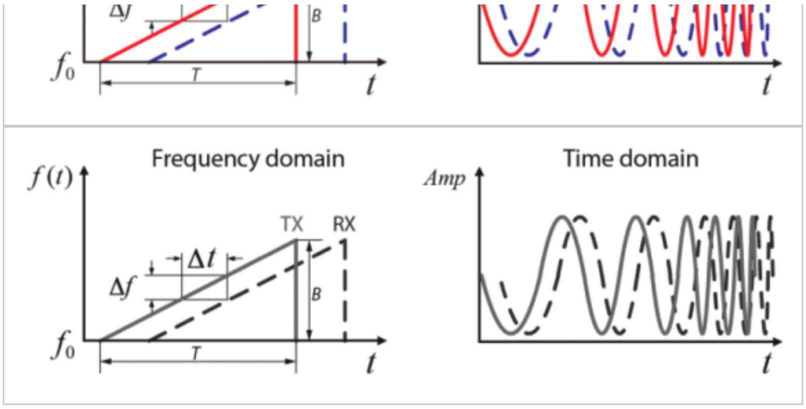


Fig. 2.
FMCW operation for range detection.

C. Hybrid-Mode Radar Systems

The frequency modulation of an FMCW radar can be turned OFF on alternate scans to identify velocity or phase information using an unmodulated radio frequency carrier, which corresponds to Doppler or interferometry mode operation. An example of a hybrid-mode waveform is shown in Fig. 3. This kind of “hybrid-mode” operation allows range and velocity to be found with one radar set. Fig. 4 illustrates an example of a portable 5.8-GHz hybrid-mode radar. In the interferometry mode, the radar transmits a single-tone signal for velocity, displacement, and micro-Doppler measurement. In the FMCW mode, the radar detects absolute range information.

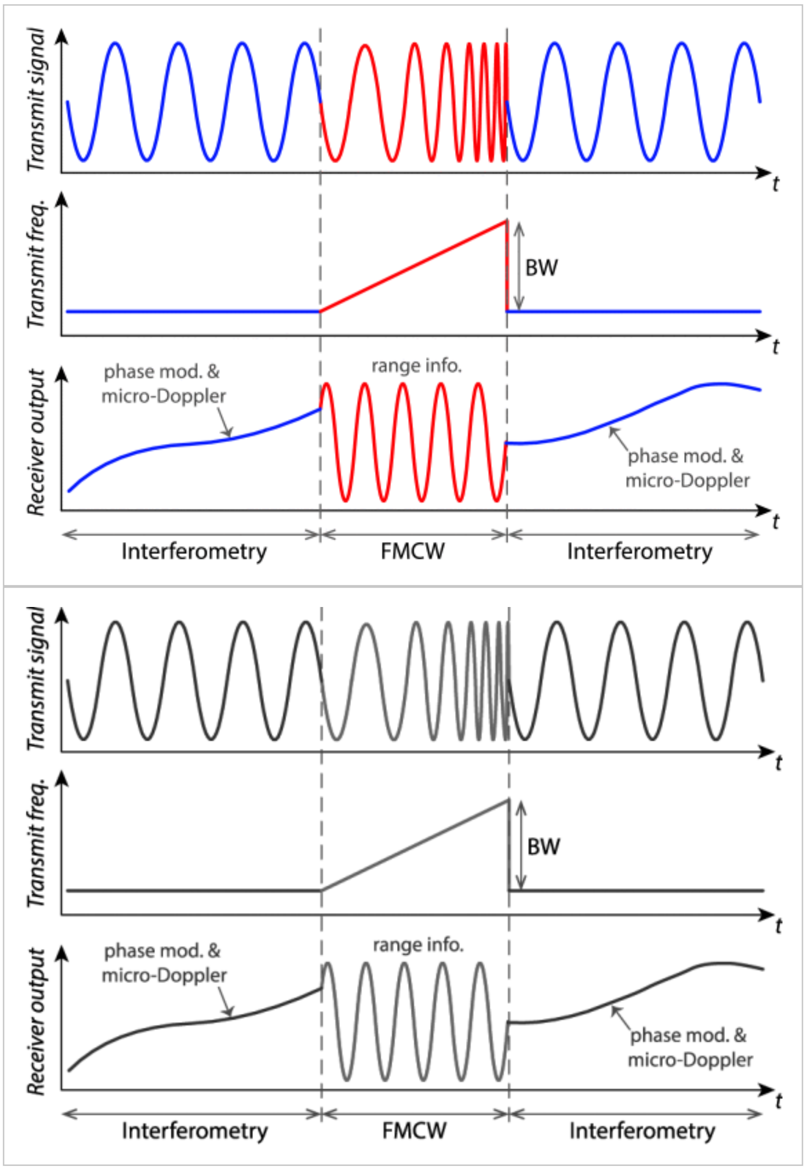


Fig. 3.
FMCW-interferometry hybrid operation mode for range and motion measurement.

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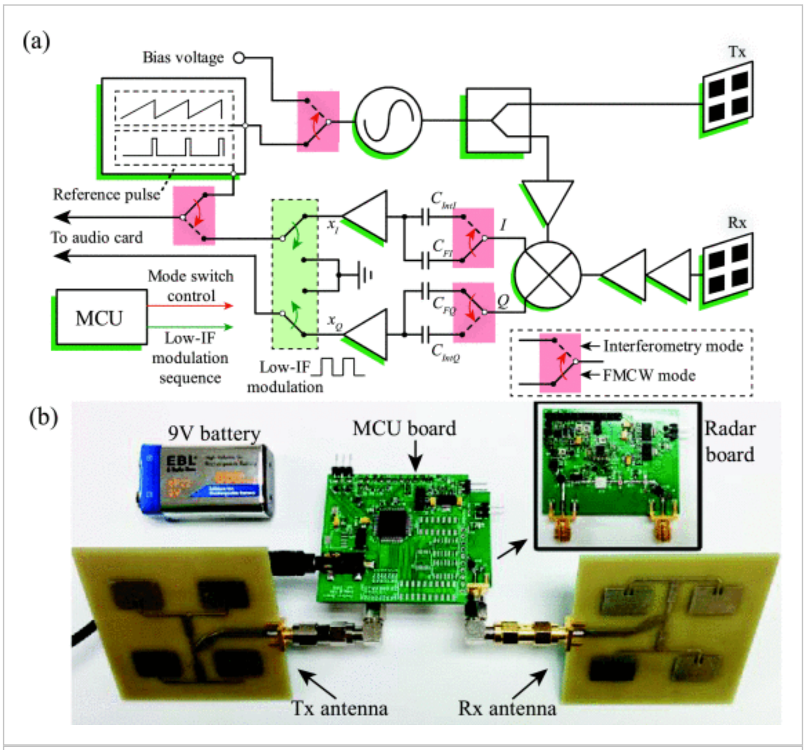

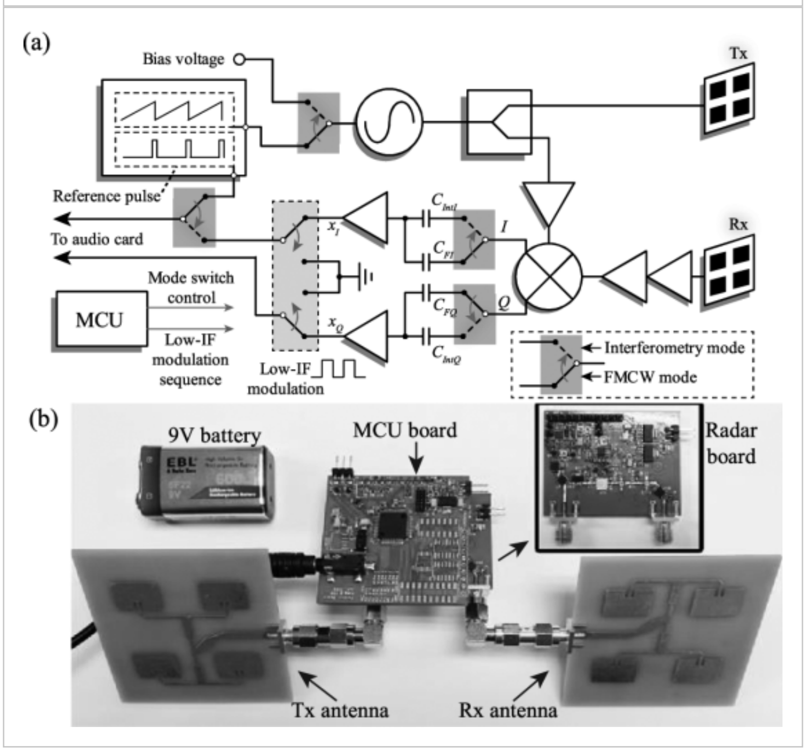

Fig. 4.
(a) Block diagram and (b) photograph of a portable FMCW-interferometry hybrid-mode radar system. Adapted from [51].

As shown in Fig. 4(a), analog switches configured by an on-board microcontroller are used to set up the radar in one of the two operational modes. For the FMCW operation, the mode switches are turned to solid line in Fig. 4(a) when the voltage-controlled oscillator (VCO) is controlled by a sawtooth-ramp voltage generated by an operational-amplifier-based circuit. The coherence property of the FMCW mode is achieved by using the reference pulse, which is also generated by the operational-amplifier-based circuit, to align the phase of each beat signal. On the other hand, when the radar is changed to the interferometry/Doppler mode, the mode switches are turned to the dash lines in Fig. 4(a) and the VCO generates a single-tone signal. In the receiver, after being amplified by the baseband amplifiers, the signals in the I/Q channels are modulated with a low-IF digital chopping signal, which is realized through the low-IF switches in Fig. 4(a) operated by a microcontroller with a constant frequency. Thus, the mechanical motion signal with low frequencies will be converted to appropriate frequency range that can be digitized by the audio analog-to-digital converter of handheld devices, such as smart phones and laptops.

D. Other Radar Systems

UWB radar systems transmit signals across a wide frequency spectrum that is typically wider than the bandwidth of conventional radar systems [52], [53]. Because the signal energy is spread in a wide bandwidth, the radar signal is usually difficult to detect, leading to low-probability-of-interception capabilities for it. A common technique for modern UWB radar is to transmit pulses with very short durations in nanosecond range or even less. While higher pulse repetition frequencies (PRFs) give rise to a higher number of returned pulses per unit time—and thus improves the average signal quality—lower PRFs avoid range ambiguities that can occur when detection distance is too large.

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Instead of transmitting an impulse directly in the time domain, stepped-frequency CW (SFCW) radars synthesize an effective bandwidth in the frequency domain. SFCW radars have been frequently used in ground-penetrating radar applications [54], [55]. In recent years, it has also been investigated for indoor-monitoring tasks, including fall detection and remote human vital signs detection [10], [56]–[57][58].

Due to the page limit and main focus of the authors' research, this paper will be focused on Doppler, interferometry, FMCW, and hybrid-mode radar. Interested readers are encouraged to refer to papers cited in this section for information on UWB and SFCW radar technologies and applications.

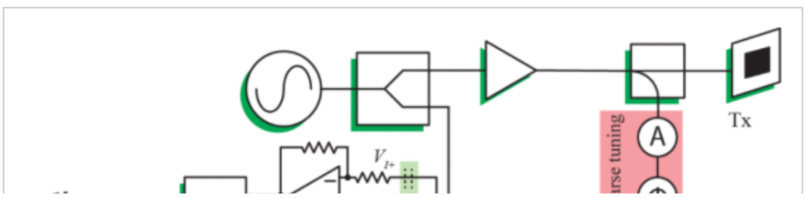
SECTION III.
Motion and Displacement Monitoring Systems

This section will be focused on portable radar systems for motion and displacement monitoring, without considering acquisition of absolute range. As a result, the radar systems introduced in this section operate on Doppler and interferometry mode, which transmits at one or a few discrete frequencies but has a high motion detection sensitivity due to the coherent phase detection and the range correlation effect [4].

A. Human Vital Signs Detection

By remotely monitoring the signal phase change due to physiological movements, interferometry-mode radars can detect respiration and heartbeat signals without requiring any sensor to be attached to the body. Their areas of exploitation also expand to speech monitoring, as reported at the end of this section. This leads to a large variety of potential applications feasible for these radar sensors, such as sleep study [59]–[60][61], baby monitors [62], [63], and searching for survivors after earthquake. While the noncontact vital signs detection concept was proposed by pioneers in this field in the twentieth century [1], [2], [64]–[65][66], research efforts in recent years have been moving the technology toward portable operation, better accuracy, and more robust operation for practical applications.

Furthermore, several studies have demonstrated that the interferometry radar could assist medical linear accelerator (LINAC) in tracking the location of a mobile tumor during lung cancer radiotherapy, to eliminate the side effect due to tumor motion caused by respiratory movement [15], [16], [67]. The challenge for this specific application, however, is the accurate measurement of the movement pattern, which is critical for the radiotherapy dose to be effectively applied to the tumor instead of surrounding healthy tissues. Since the respiratory signal to be detected has a very low frequency and even dc component (i.e., a stationary moment after the end of exhalation), it will be distorted by the coupling capacitor between the mixer and baseband amplifier in the receiving chain. This is illustrated in Fig. 5. Simply connecting the mixer output and baseband amplifier would not help because the baseband circuit may be easily saturated due to the dc offset produced by down-conversion of clutter reflection and TX-to-RX leakage. To resolve the problem, a dc-coupled radar with dynamic tuning solution was developed based on a coarse tuning that cancels clutter reflection at the receiver input and a fine tuning that further adjusts the dc bias point of the baseband circuit [15]. A 2.4-GHz portable version of the design is modeled as "iMotion2" and tested on a medical LINAC when the radiation beam is turned ON. Fig. 6 shows the test setup with a motion phantom as the target and an infrared camera to provide the reference. The result in Fig. 7 shows that the radar can precisely measure motion pattern with submillimeter accuracy.



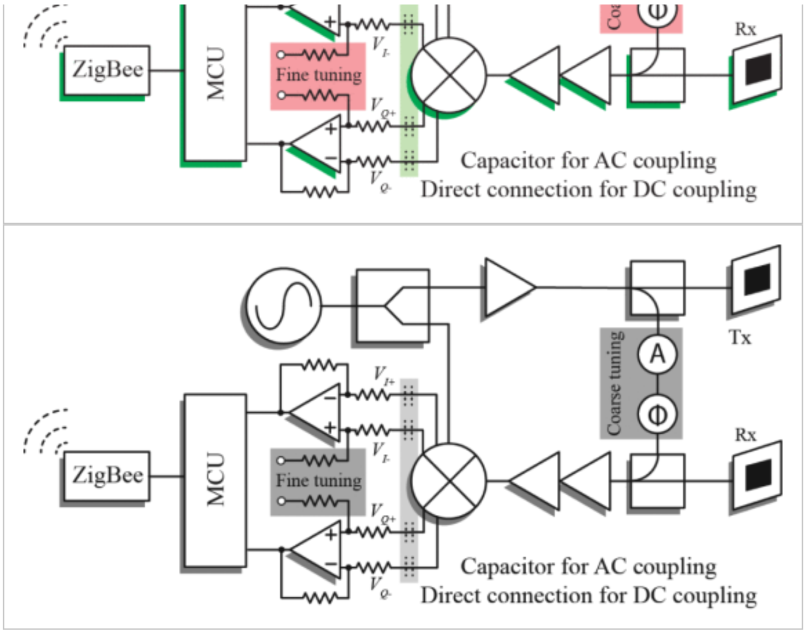


Fig. 5.
Block diagram of a 2.4-GHz dc-coupled displacement radar (*iMotion2*) for respiratory monitoring during radiotherapy.

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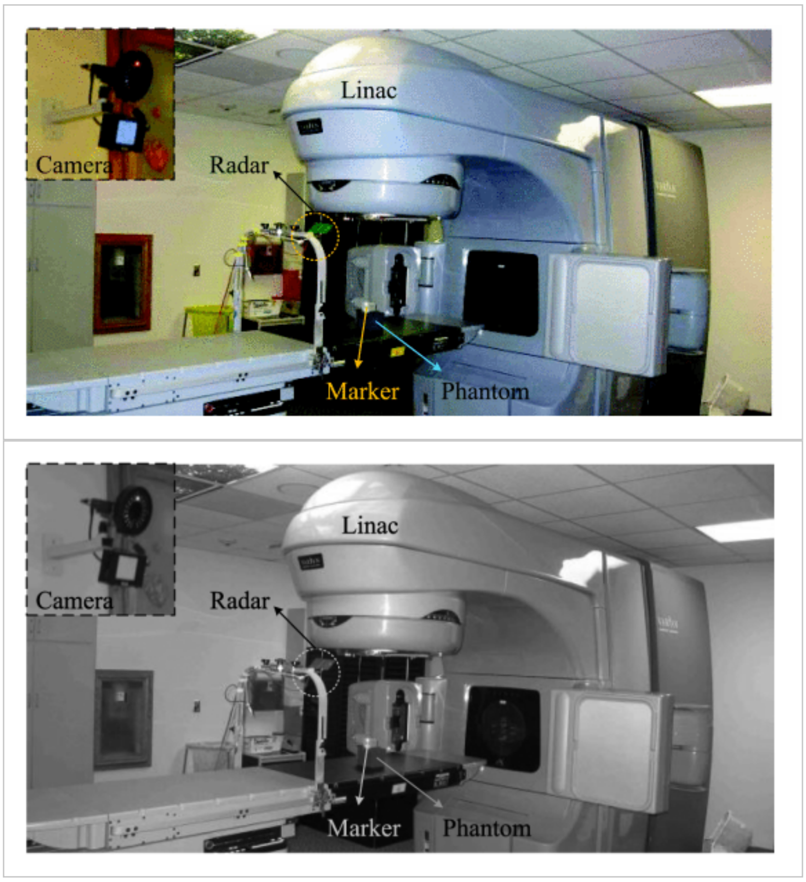
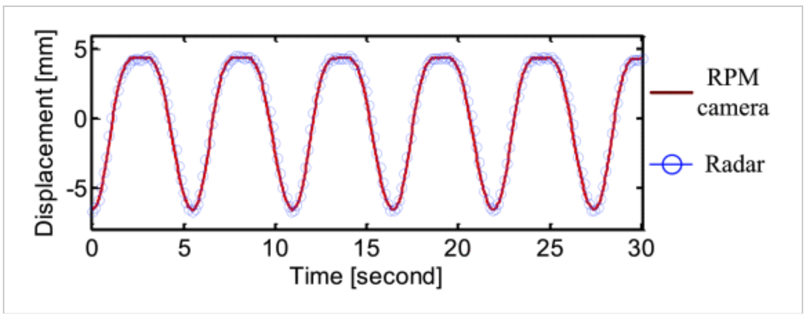


Fig. 6.
Experimental setups with a motion phantom measured by a camera and a radar sensor. From [15].



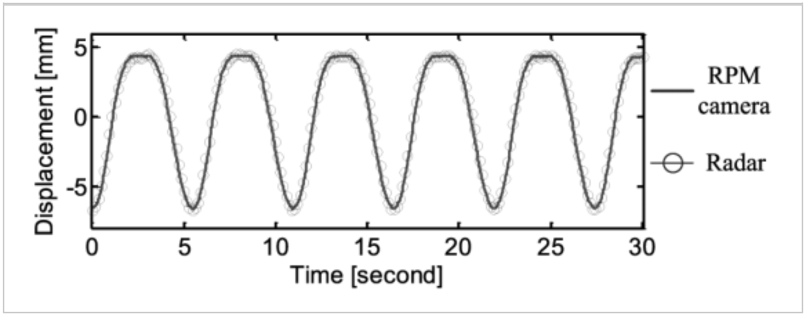


Fig. 7.
Phantom motion measured by the radar with the LINAC radiation beam turned ON and comparison with the same phantom motion measured by Varian's RPM system. From [15].

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However, the tradeoff found in employing a dc-coupled radar with dynamic tuning is the necessity of monitoring the baseband output dc level and adjust the coarse tuning and fine-tuning in real time, which increases the operation cost. An alternative was recently developed by implementing a postdistortion algorithm to compensate for the frequency-dependent distortion in the baseband output of an ac-coupled radar [68]. The solution can be implemented in software with a low computational load to enable conventional ac-coupled Doppler radar for accurate movement pattern detection.

B. Veterinary Monitoring and Animal Study

Animal experiments are conducted for various purposes in veterinary medicine, including production and quality control, toxicology and safety tests, and fundamental biomedical research. Most of animal experiments are conducted with mice and rats due to their similarities to human biology, genetic consistency, short lifespan, and quick reproduction [69]. The assessment of cardiorespiratory parameters is crucial in animal testing for studying pathology and developing new treatment. In order to monitor cardiorespiratory activities during animal testing, conventional methods, such as tail-cuff, tether system, indwelling arterial catheter, and implant telemetry, are being used. However, surgical implantation and body-restrained contact also result in increased risk of infection and unintended effect. To overcome the limitations of conventional methods, the technique of using Doppler radar has been proposed. The radar technique can provide noninvasive and noncontact monitoring without the need of cleaning or disposing devices after use. It can reduce animal use by providing long-term monitoring of the same animal and is a useful tool for studying the biological effects in drug development.

The challenge of measuring a small animal's cardiorespiratory activity with radar is its tiny chest wall movement. It is true that millimeter-wave operating frequency (i.e., short wavelength) can be used to increase the sensitivity for detecting small vibrations. However, the strong harmonics caused by the nonlinear Doppler phase demodulation method also complicates the detected spectrum [70]. Although rats have smaller chest-wall displacements compared to humans, the nonlinearity arises in the demodulation process due to the comparable wavelength to the small displacements [70]. By exploiting the harmonics produced by the demodulation method, both frequencies and displacements of both heartbeat and respiration movements of the laboratory rat can be successfully measured [71].

The measurement was performed with a 60 GHz radar [72] to demonstrate the efficacy of noncontact and noninvasive vital sign detection in a laboratory rat. As shown in Fig. 8, the radar was placed in front of the rat housed in a cage, and the sampled I/Q signals [DAQ, 12-b 10000 sample/s; National Instruments (NI)] were then sent to a computer. Fig. 9(a) shows the radar-measured spectrum of a laboratory rat. To properly choose the demodulation-generated harmonics shown on the spectrum, the harmonic-frequency tones produced by the respiration rate (RR) and heart rate (HR) are sorted into two groups to identify the RR and HR and then perform additional data processing to extract displacements [3]. Table I shows the measurement results and calculated displacements of heartbeat and respiratory movements based on Fig. 9(a). The amplitude of harmonics is expressed as H_x , and $J_n(a=4\pi m/\lambda)$ is the n th-order Bessel function, m is the vibration displacement, and a_h and a_r represent heartbeat and respiration coefficients, respectively. Fig. 9(b) and (c) shows the variations of frequencies and displacements, respectively, in a 47 s recording time period. The experimental results clearly show the cardiorespiratory activities of a lab animal using microwave radar, which provides useful information without using implant devices. In addition to the measured RR and HR, the calculated displacement can be used to construct an adaptive harmonics cancellation technique to enhance the accuracy of heartbeat detection [73].

TABLE I Measurement of a Laboratory Rat Using Radar

	Measured Rate	DG Harms Ratio	Calculated m
Respiration	39.6 Breath/min	$\frac{H_{RR}}{H_{2RR}} = \frac{J_1(a_r)}{J_2(a_r)}$	1.19 mm
Heartbeat	403.8 BPM	$\frac{H_{RR}}{H_{HR-RR}} = \frac{J_0(a_h)}{J_1(a_h)}$	0.13 mm

	Measured Rate	DG Harms Ratio	Calculated m
Respiration	39.6 Breath/min	$\frac{H_{RR}}{H_{2RR}} = \frac{J_1(a_r)}{J_2(a_r)}$	1.19 mm
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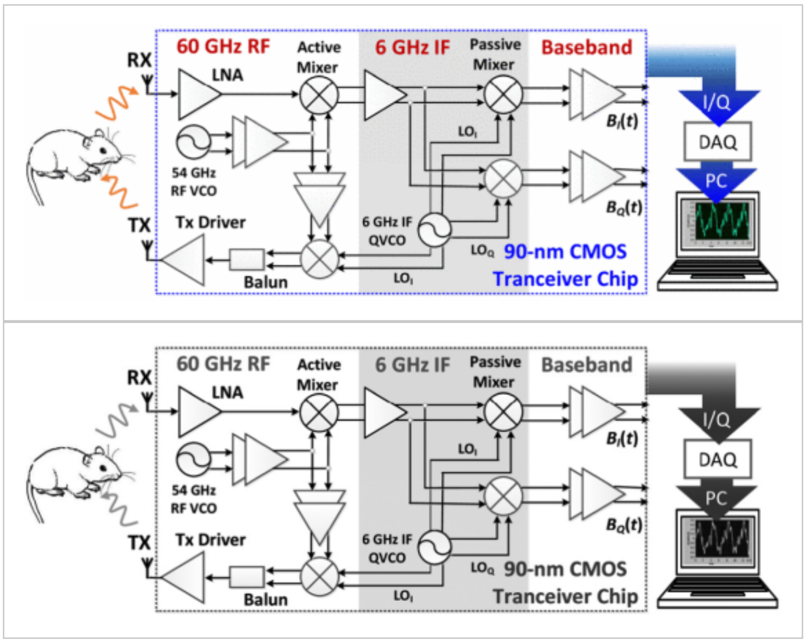
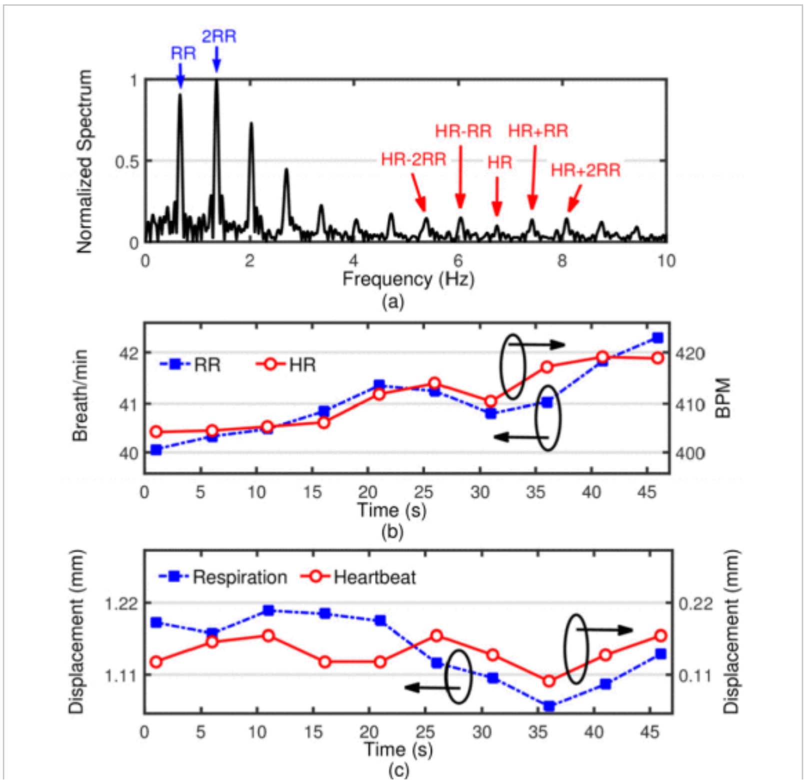


Fig. 8.
Experimental setup for measuring cardiorespiratory movement of a laboratory rat using a 60-GHz microradar. From [71] and [72].



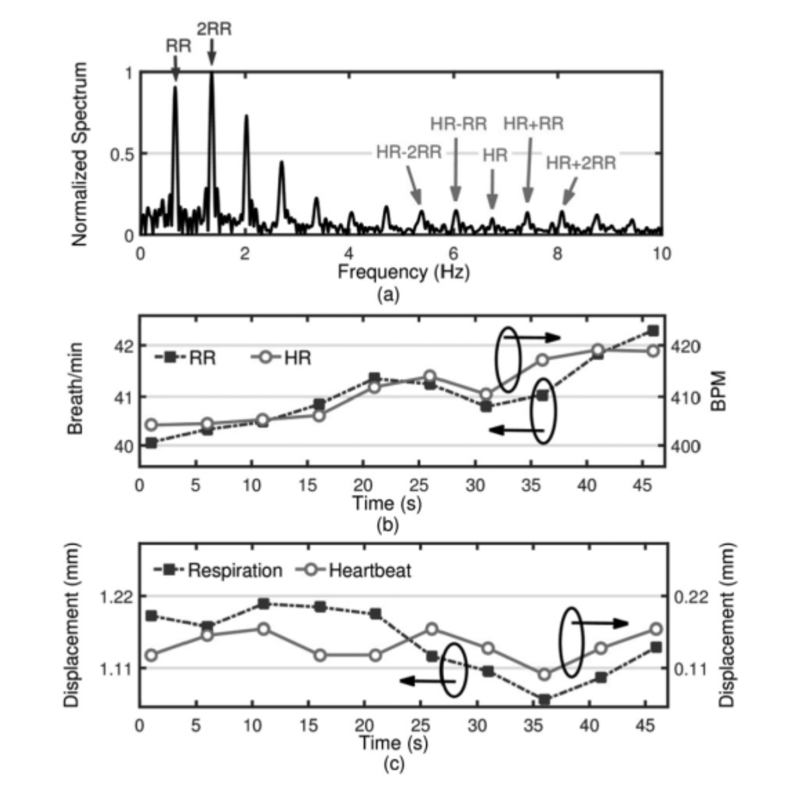


Fig. 9.
(a) Radar-measured baseband spectrum of a laboratory rat's vital signs. (b) RR and HR versus time. (c) Displacements of both respiration and heartbeat movements. The figures are replotted from [71].

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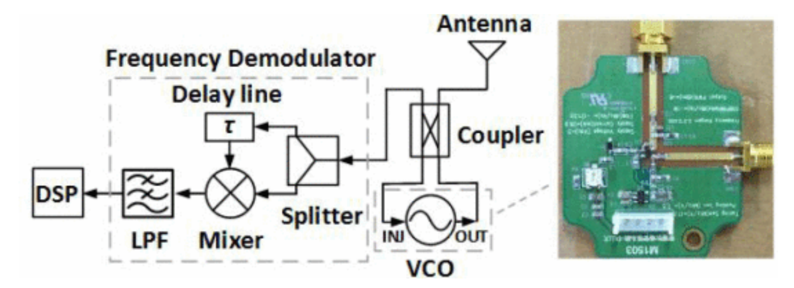
Recently, self-injection locked (SIL) radar has garnered attention due to its high sensitivity to vital sign detection [74], [75]. In its basic operation, a VCO transmits a CW signal, which is partially reflected by a distant biological object, and then injected into the same VCO to form an SIL state. The Doppler modulation that is related to the object's physiological movement can be simply extracted by frequency demodulation of the oscillator output. Since there is no mixing between RF and local oscillator signals in the reception process, the SIL radar is inherently immune to stationary clutter, such as that produced by background reflection and antenna coupling. Due to this advantage, the SIL radar has attracted great interest from the livestock industry and is actively being exploited to monitor animal health in harsh backscattering environments, such as the monitoring of cow's vital signs in a barn where metallic fences are largely used. Furthermore, the SIL radar uses a single antenna to transmit the CW signal and then receive the echo signal without the need to isolate both signals. This benefit avoids the trouble of setting up two antennas, particularly two high-gain antennas.

Fig. 10 shows the block diagram of a prototype SIL radar system that was built for licensing to dairy companies. The system, operating at 2.4-GHz ISM band, comprises an antenna, a VCO with an injection terminal, a coupler, a frequency demodulator that is composed of a splitter, a passive mixer, a delay line and a lowpass filter, and a digital signal processing (DSP) unit. In the RF circuit of this system whose photograph is shown in Fig. 10, the VCO is the only active component while the others are the passive coaxial components from commercial off-the-shelf products. This VCO, fabricated on an FR4 substrate, uses a Clapp configuration along with an injection port connected to the gate of the transistor. It has a tuning range from 2.3 to 2.65 GHz and an output power level of 5 dBm under a power consumption of 140 mW. All the RF circuit components are housed together in a rugged metallic box for protection from cow manure splash.



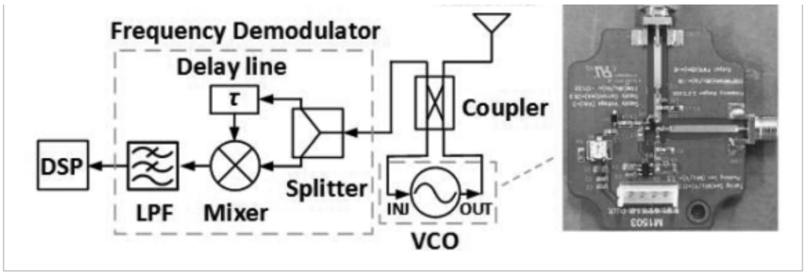


Fig. 10.
Block diagram of a prototype SIL radar system.

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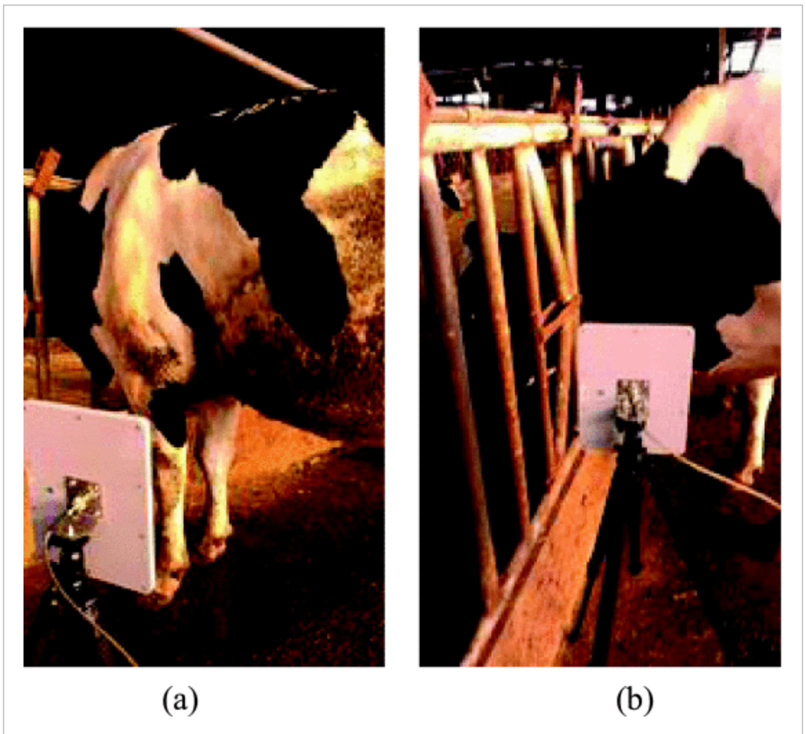
In health monitoring for cows, RR and pulse rate are important because they tell if cows are feverish, or hot or normal. To measure these two rates, the antenna beams are empirically directed to the belly and neck of the cow as shown in Fig. 11(a) and (b), where the movements caused by the respiration and the carotid artery pulse, respectively, are most significant. In Fig. 11(a) and (b), a high-gain antenna of 18 dBi was used for the radar system to detect RR or pulse rate at one meter away from the cow. The RF processing yields a Doppler signal that is associated with the movement of the antenna's illumination area on the cow. Following further DSP operation, the time–frequency spectrogram of the signal is constructed and used to identify the respiration or pulse frequency when the cow is stationary. Then, a bandpass moving average filter is employed to emphasize the spectrogram at the identified frequency [9], as illustrated by the results shown in Fig. 12(a) and (b) for the measurement on the belly and neck, respectively, of the cow. In Fig. 12(a) and (b), the diffusion phenomena of the target frequency lines are mainly caused by the residual motion artifacts after filtering. Nevertheless, a frequency line of about 0.75 and 1.2 Hz, corresponding to an RR of 45 beats/min and a pulse rate of 72 beats/min, respectively, is observed in the figures over a period of 280 s. The pulse frequency line is more diffuse than the respiration one because the neck moves more greatly and frequently than the belly. It is noted that the obtained RR and pulse rate of the cow from the radar system were verified by a veterinary using a stethoscope on the chest area of the cow.



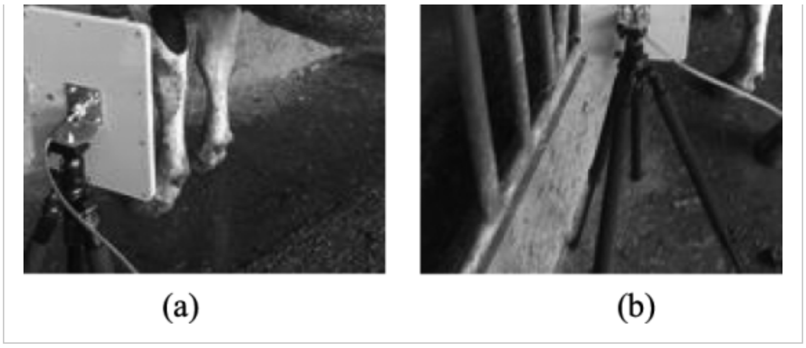


Fig. 11.
Detection of vital signs on different areas of a cow. (a) Belly. (b) Neck.

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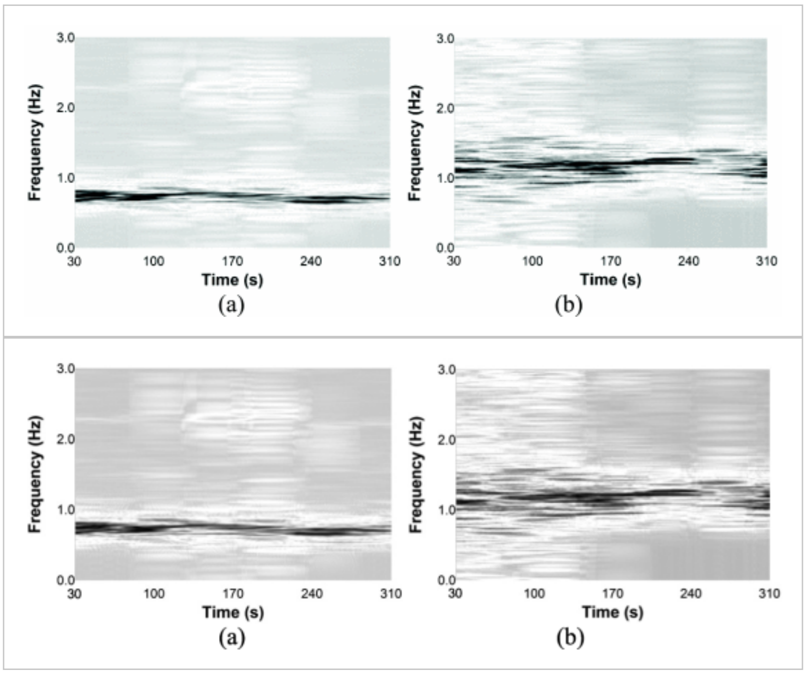


Fig. 12.
Spectrograms with bandpass moving average filtering to enhance the vital sign frequencies of the cow. (a) Respiration. (b) Pulse.

Doppler radar has also been applied to monitor the health and behavior of other animals, including lizards and fish. Interested readers are referred to [76]–[77][78] for details.

C. Structural Vibration Monitoring

Aging of infrastructure has raised worldwide concerns. Multiple sensing solutions are being investigated to provide continuous SHM [79]. For example, accelerometers have been used for vibration measurement, but they suffer from degraded performance for slow movements and displacements [80], [81]. Contact displacement sensors, such as linear variable differential transformers, provide accurate measurements but require attachment to a fixed reference point, leading to complex installation setup that is not suitable for most field applications [82]. CW radar sensors are a promising technology for displacement and vibration measurements for SHM, as the previous sections have already demonstrated the capability of high accuracy noncontact measurement for slow movement. Some researchers have used noncontact microwave interferometers to measure the displacement vibration response of a steel plate girder bridge [82]. The sensors consisted of a 61 cm parabolic dish placed under the bridge and pointing back to a portion of the underside of a single plate girder, with the cost of each prototype at U.S. $1000 in 1997. Other researchers tried to use radar-based sensors to measure structural deflections, but the solution uses complex hardware with very high sampling rates [83]–[84][85]. In addition, the system could not differentiate targets at the same distance (i.e., no cross-range resolution) due to the backscattering detection mechanism.

To solve the problem of backscattering radar, recently researchers proposed implementing portable radar sensors along a bridge, and use active transponders under a bridge as reference points, to precisely track the vibration and displacement for each critical point on the bridge. An implementation block diagram is shown in Fig. 13. Compared with passive backscattering, the active transponder configuration is capable of increasing the power or changing the frequency of signals reflected from reference points, thereby significantly suppressing the influence of undesired signals reflected from reference points, thereby significantly suppressing the influence of undesired reflection from surrounding clutter (e.g., moving objects near the bridge). Because clutter reflection is mitigated, it also significantly relaxes the requirement on antenna directivity, thus making SHM possible using miniaturized radar sensors that operate in GHz range for longer operation range and lower cost compared with millimeter-wave radar sensors.

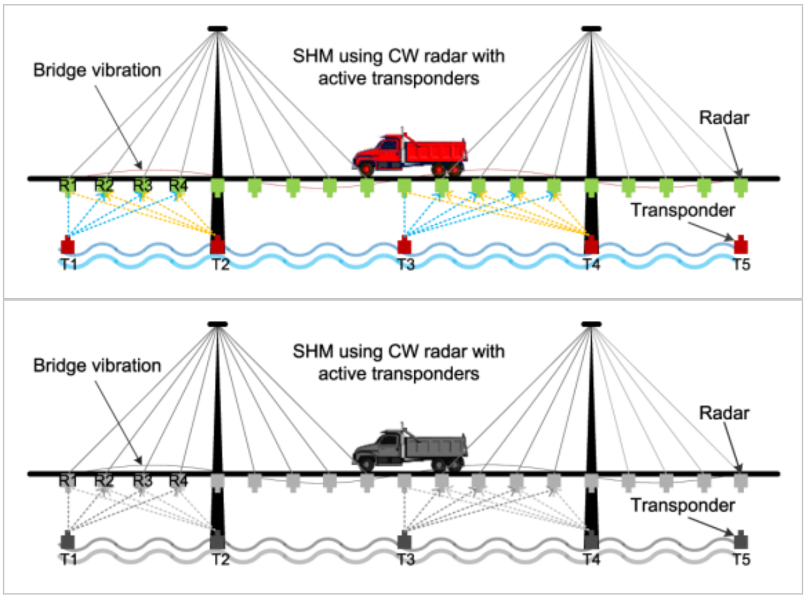
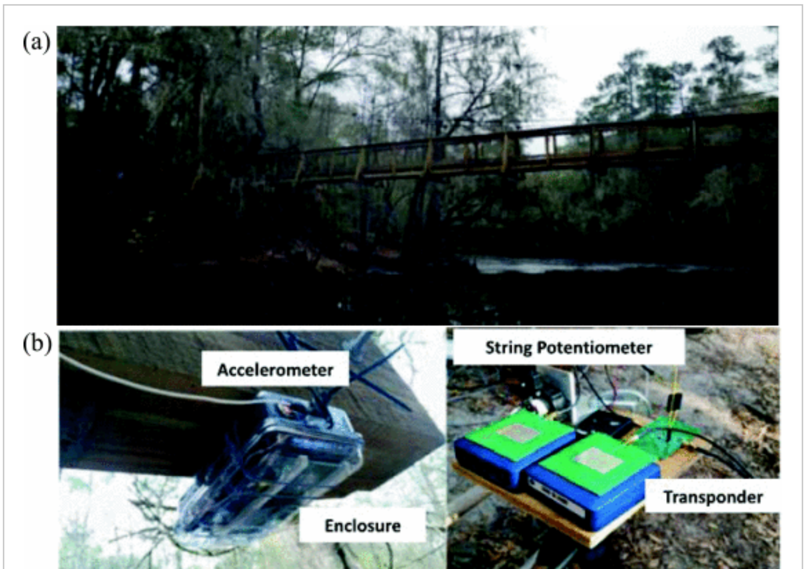


Fig. 13.
Concept of using a distributed radar sensor network to monitor the vibration and deflection of a long span bridge.

A series of laboratory experiments to demonstrate the performance of the transponder configuration has been conducted in [19]. The investigation revealed that the signal improvement provided by the transponder is a function of the distance between the transponder and the radar. In addition, a full-scale bridge test was conducted at the O'Leno State Park in Florida, USA, which is shown in Fig. 14. The test was set up at the quarter span of the bridge directly over one of the embankments. The radar was housed in a weatherproof enclosure and attached to the bottom side of the beam with its antenna facing toward the ground surface. A transponder was placed 248 cm from the radar on the ground directly below the radar. To validate the measurements obtained from the radar/transponder, a string potentiometer and a single-axis accelerometer (PCB Piezotronics, 1000 mV/g sensitivity, sampled at 500 Hz) were installed at the same location. One end of the string potentiometer was connected to the radar enclosure, and the other end was attached to the tripod hosting the transponder. The bridge was excited by a person jumping at a location close to the quarter span, with a frequency close to the first natural frequency of the bridge. All the sensors simultaneously measured the resulting vertical motion of the bridge at the quarter span.



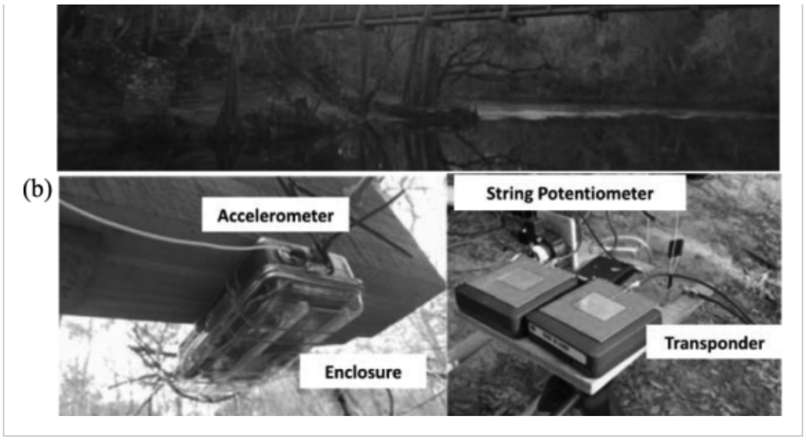


Fig. 14.
(a) Experimental setup of the full-scale bridge test at O'Leno State Park in Florida, USA. (b) 2.4-GHz DC-coupled radar enclosure with an accelerometer and the transponder. From [19].

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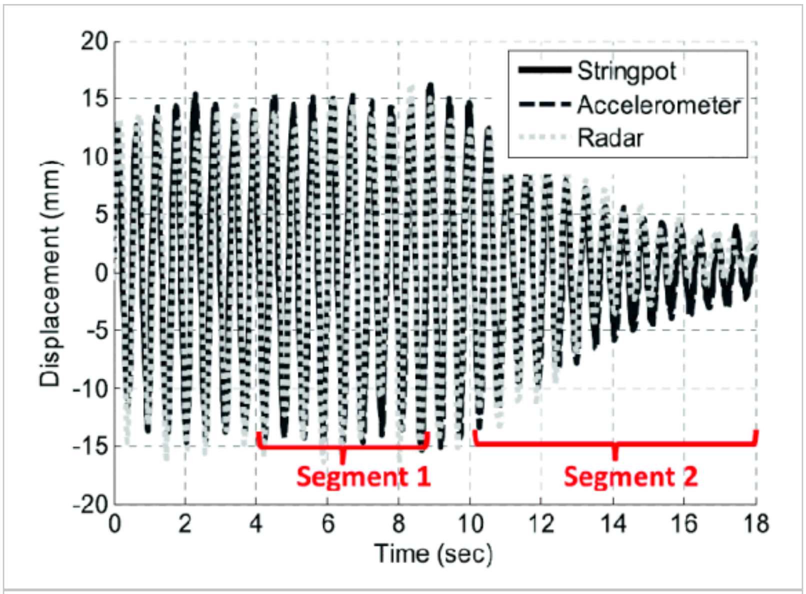
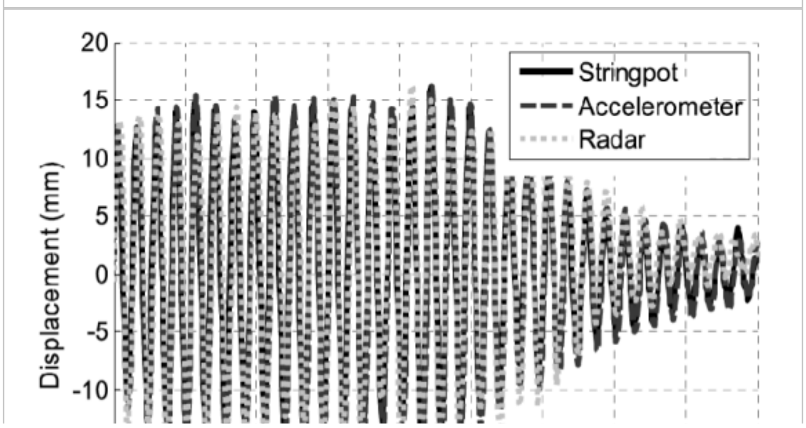
The displacement measurement results are shown in Fig. 15. The result from the accelerometer was obtained by double-integrating the measured acceleration and passing the results to an equiripple finite-impulse response high-pass filter with a cutoff frequency of 0.1 Hz. Otherwise, the low-frequency noise of the accelerometer would be amplified during the integration process. With the help from the transponder, the dc-coupled radar successfully measured both the constant amplitude motion (segment 1, less than 1 mm error) and the decaying amplitude motion part (segment 2, less than 2 mm error) of the bridge vibration, in comparison with the other sensors. On the other hand, when the transponder is turned OFF, the radar working in passive scattering mode was unable to reliably measure the motion. It should be noted that, due to practical nonidealities such as insufficient suppression of clutter noise, although the full-scale bridge test successfully demonstrated the advantage of active transponder mode of portable radar for SHM, it did not confirm previous lab results showing potential advantages of radar sensors over accelerometers [86]. Continuing efforts are then needed from industrial and academic researchers to further improve the performance. Potential research areas in this context include increasing the detection range, reducing beamwidth without increasing antenna size, and developing frequency-conversion transponders that will have better clutter/noise rejection.





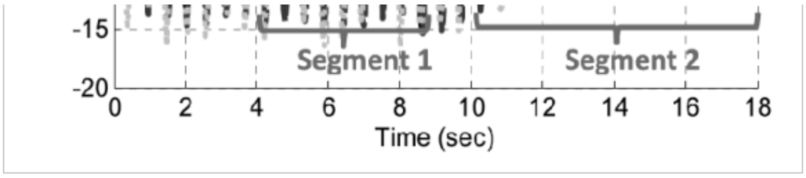


Fig. 15.
Time history record of displacement measurement results from all the sensors. From [19].

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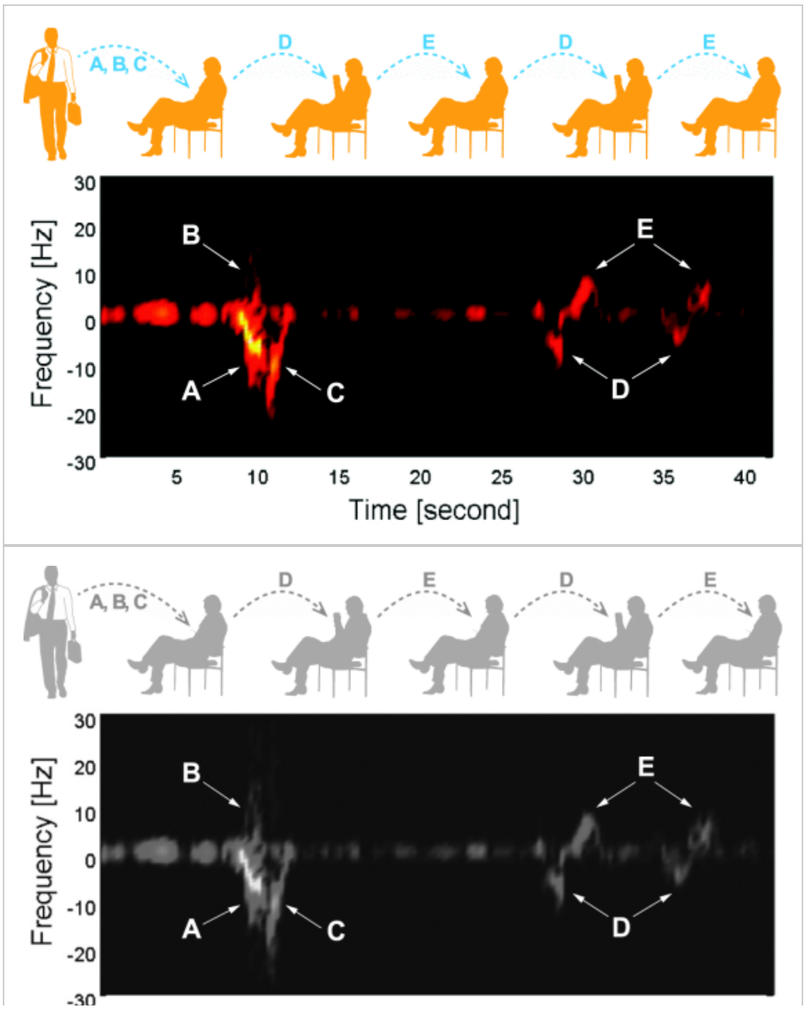
D. Gesture Characterization Using Time–Frequency Analysis

Time–frequency analysis studies a signal over both time and frequency by mapping a 1-D signal into a 2-D representation of energy versus time and frequency. Analysis of the radar-detected signal in both time and frequency domains can reveal features of a movement for classification purposes [20], [21], [87], [88]. Especially, local mechanical vibrations or rotations of a target or part of a target may induce additional frequency modulations as a function of time, causing the micro-Doppler effect [89]. For example, Fig. 16 shows the micro-Doppler when a person sat down, and raise and put down one hand twice [90]. Original research in this area was mainly based on relatively bulky bench top radar systems or modules. In recent years, because of the advancements of semiconductor technologies and embedded computation, it became possible to use small portable radar devices to analyze motion features in time–frequency domain for the Internet of Things (IoTs) applications. In one example [91], a portable smart radar gesture recognition sensor achieved 96.7% accuracy for identifying different types of hand movements and head movements. The device was able to differentiate hand lifting and hand pushing based on four features extracted from the measured results. Not only academia, but the information technology industry is also working on gesture recognition using integrated devices for IoT applications. In May 2015, Google launched to public the project *Soli*, which aims to develop robust, high-resolution, and low-power miniature gesture sensing technology for human-computer interaction based on millimeter-wave radar [23]. The team's solution was based on an integrated millimeter-wave radar sensor chip, a high temporal resolution gesture tracking, a hardware abstraction layer, interaction models, and gesture vocabularies. Demonstration showed a submillimeter accuracy and a speed of 10000 frames/s on embedded hardware. Other companies are also investigating applications of radar-based gesture characterization. For example, NVIDIA Research developed a short-range FMCW monopulse radar for hand-gesture sensing as a key element in intelligent driver assistance systems [92].



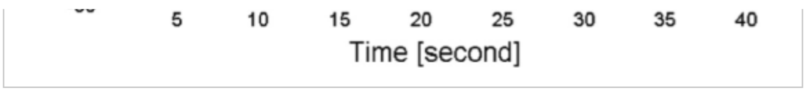


Fig. 16.
Micro-Doppler information when a person sat down (A, B, C) and waived hands twice (D, E). Adapted from [90].

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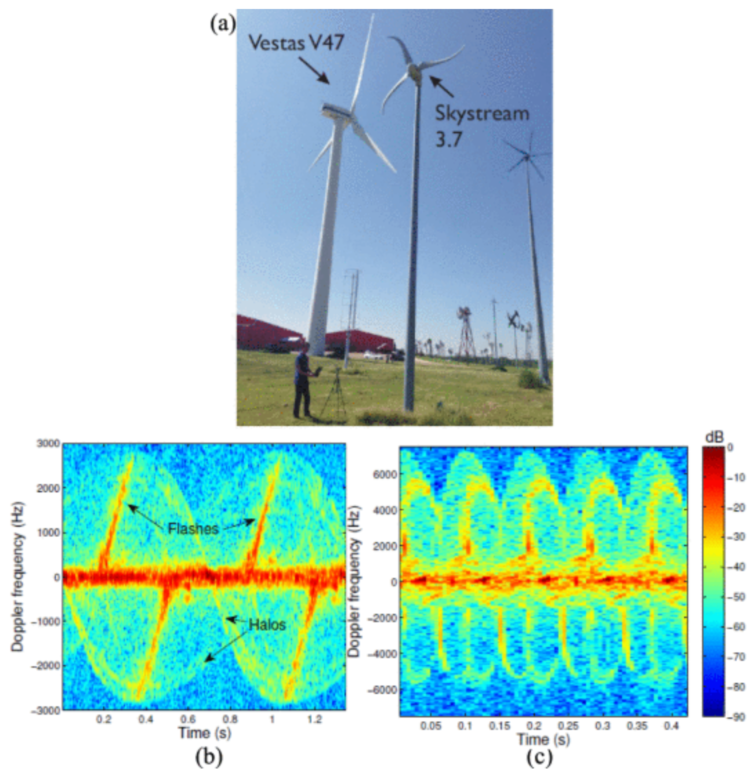
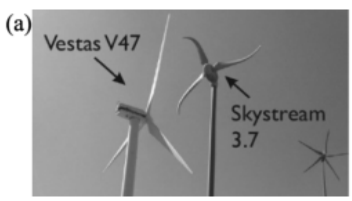
E. Turbine Blade Monitoring

As wind turbines increase in size and cost, there is a growing need for early detection of structural and mechanical problems to avoid further damage. It is shown that blade damage is the most expensive one to repair and has the longest repair time [93]. Without prompt correction, rotating mass unbalance due to minor blade damage can also cause serious secondary damage to the system. Common detection methods for rotor imbalance examine variation in rotor speed and transverse oscillations of the nacelle [94]. The acoustic emission method is used during laboratory fatigue cycle tests of blades [95]. Optical systems have been developed for delineating the global shape of large blades [96] while fiber-optical sensors are embedded in wind turbine blades and collect information regarding strain, temperature, and curvature [97].

As a noncontact solution, low-cost low-profile radars are gaining interest for providing real-time structural information on a large number of wind turbines. Using time–frequency analysis, Doppler features can be investigated for each blade while a turbine is running [24], [25]. Fig. 17 shows an example using 5.8- and 24-GHz portable radar sensors to monitor wind turbines in the American Wind Power Center, Lubbock, TX, USA [26]. The 5.8-GHz radar is the hybrid mode radar discussed in Fig. 4 operating in the Doppler mode, whereas the 24-GHz radar is shown in Fig. 18. Two different turbines were measured: a 660-kW Vestas V47 wind turbine with a 47-m rotor diameter and a 1.9-kW Skystream 3.7 wind turbine with a 3.7-m rotor diameter. It should be noted that the Vestas V47 turbine has straight blades while the Skystream 3.7 turbine has curved blades. On the returned spectrograms in Fig. 17(b) and (c), it is clearly shown that different blade shapes induced different features for the spectrogram flashes, verifying the feasibility to monitor the shape and distortion of turbine blades with low-cost portable radar sensors while a turbine is operating. Interested readers are referred to [26] for detailed discussions on practical issues, such as the optimal acquisition angle, the generation of flashes on the spectrogram, the correspondence between the flash shape and the blade shape, the effect of energetic scatterer, and the effect of I/Q mismatch in the portable radar.





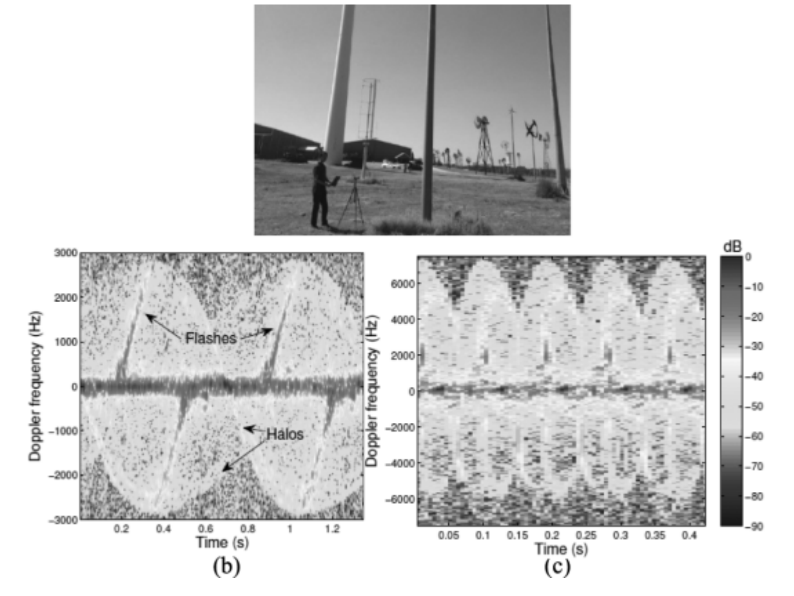
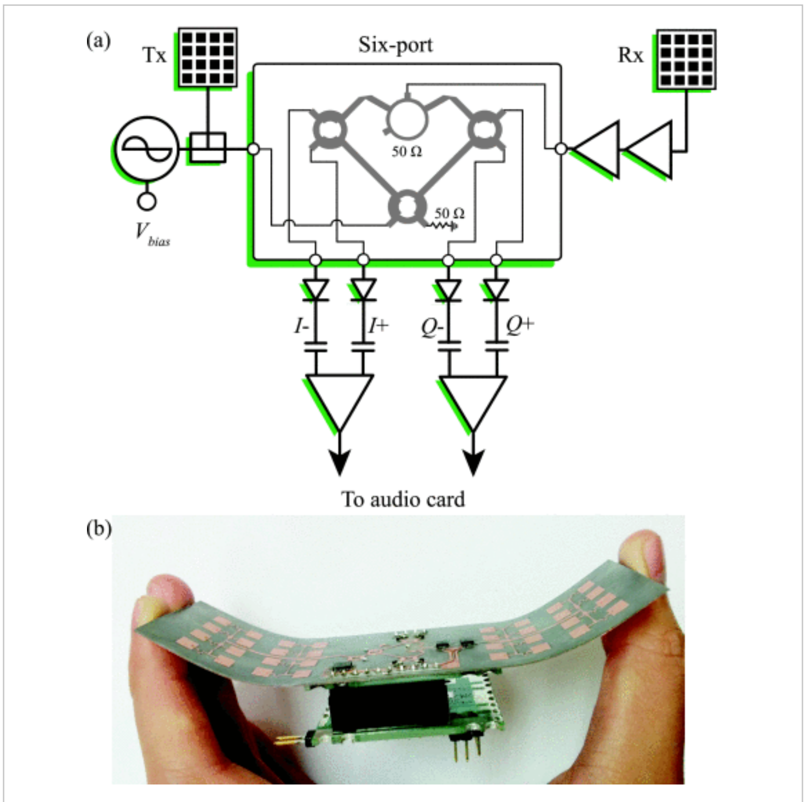
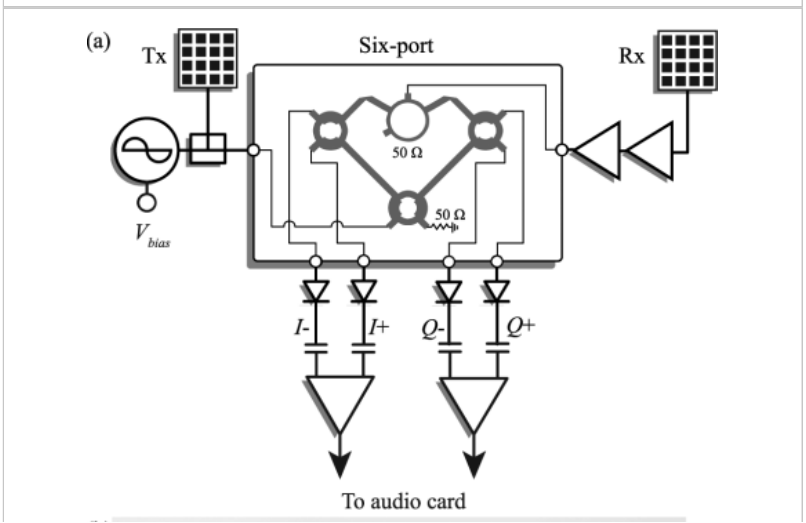


Fig. 17.
(a) Using portable radar to measure a Vestas V47 wind turbine with straight blades and a Skystream 3.7 wind turbine with curved blades. (b) Time–frequency signature of Vestas V47 turbine blades measured by a C -band radar. (c) Time–frequency signature of Skystream 3.7 turbine blades measured by a K -band radar. From [26].





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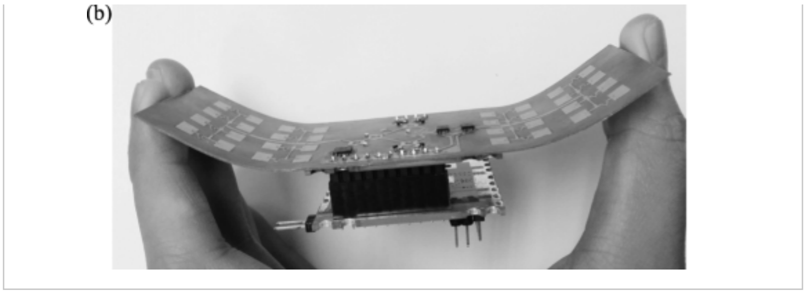

Fig. 18.
(a) Block diagram and (b) photograph of a 24-GHz radar on flexible substrate for monitoring of wind turbine blades.

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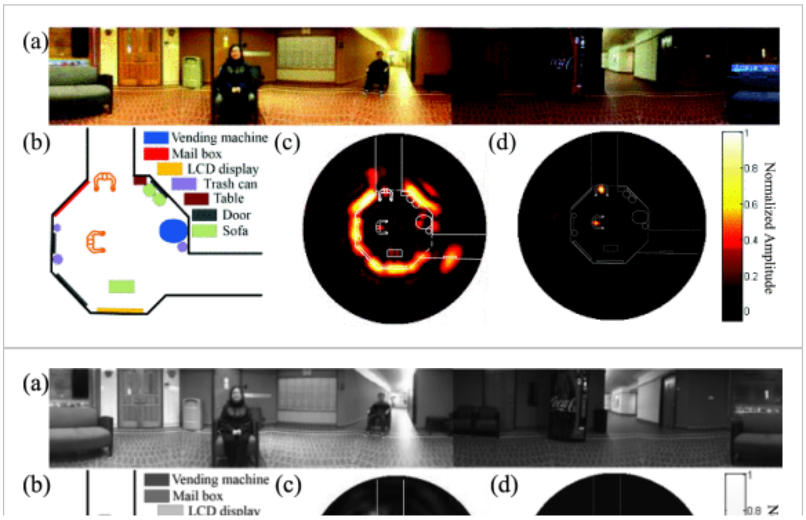
F. Other System Realizations and Applications

Taking advantage of the millimeter or submillimeter sensitivity that can be easily achieved using GHz-range Doppler/interferometry radars, many more applications have emerged with the help of various back-end signal processing methods proposed in recent years. For example, Wang *et al.* [98] used an extended differentiate and cross-multiply algorithm to demodulate the detected baseband signal and recover the original vibration information, enabling the detection of a failure (i.e., undesired speed change) in a mechanical vibration with 12-mm amplitude. Using time–frequency analysis [14] and a variational mode decomposition-based algorithm [12], directional discrimination, background noise rejection, and vocal folds vibration detection were realized for portable auditory radars. In two high-sensitivity radar design competitions held in the International Microwave Symposium in 2014 and 2015, researchers from multiple countries have demonstrated various portable low-power motion detection radars covering a broad frequency range from 2.4 to 80 GHz. The designs of two teams can be found in [99] and [100].

SECTION IV.
Localization and Tracking Systems

A. Indoor 2-D Mapping Using FMCW and Hybrid Systems

The FMCW-interferometry hybrid mode works in a "burst-FMCW" fashion, where short-time range spectrum analysis can be carried out for a single FMCW chirp in an embedded digital signal processor, thus obtaining satisfactory range estimation with a good signal-to-noise ratio. By pointing a portable device to different directions or steering its signal beam electronically, capability to map an indoor environment would be enabled. On the other hand, the interferometry mode offers very high motion detection sensitivity (i.e., millimeter or submillimeter motion detection sensitivity with GHz carrier signals) at a low computational load, which facilitates activity monitoring. Fig. 19 shows a demonstration of 2-D human-aware indoor mapping based on this idea [90]. With FMCW operation, the hybrid radar can detect the hallway layout with both furniture and human targets as shown in Fig. 19(c). The interferometry mode together with deramping-based FMCW analysis can differentiate between humans and other objects based on physiological motion, and thus identify the human targets as shown in Fig. 19(d) [90]. Although the result of Fig. 19 was obtained from a system including a desktop NI PXI-based signal generator, similar localization and human identification results can be obtained using portable devices such as the 5.8 GHz hybrid-mode radar shown in Fig. 4.



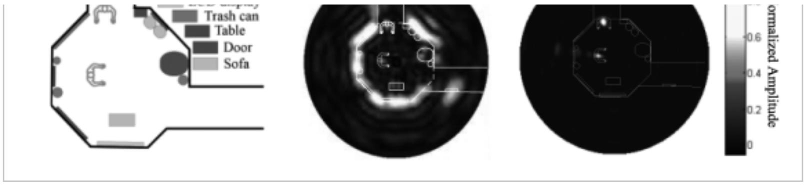


Fig. 19.
Indoor positioning and human identification. (a) Experiment setup. (b) Room layout. (c) 2-D positioning map obtained in FMCW detection mode. (d) Result of human tracking based on vital signs. Adapted from [90].

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B. Range-Doppler Tracking and Fall Detection

ISAR is a radar technique based on a 2-D high-resolution image to track a target [101]–[102][103]. ISAR images are often produced by rotating the target and processing the resultant Doppler histories of the scattering centers. The same principle of analyzing Doppler histories of a target at a given range can be used for indoor tracking. The mechanism is shown in Fig. 20. A coherent FMCW radar detects a signal that can be arranged in a slow-time versus fast-time matrix. Performing Fourier transform along the fast-time finds the beat frequency, which converts the fast-time information into range information. After that, the range-profile history is divided into running windows along the slow time. Performing Fourier transform along the slow time for each window converts the slow-time range variation into Doppler information. As a result, a series of range-Doppler history can be obtained for the running windows, which can form an “ISAR video.” It should be noted that the ISAR video discussed in this paper is different from a conventional ISAR image: ISAR image requires rotating the target to illustrate the detailed profile of a target, whereas the ISAR video used in this section can differentiate moving targets in the range-Doppler domain even if they are moving linearly without any rotation.

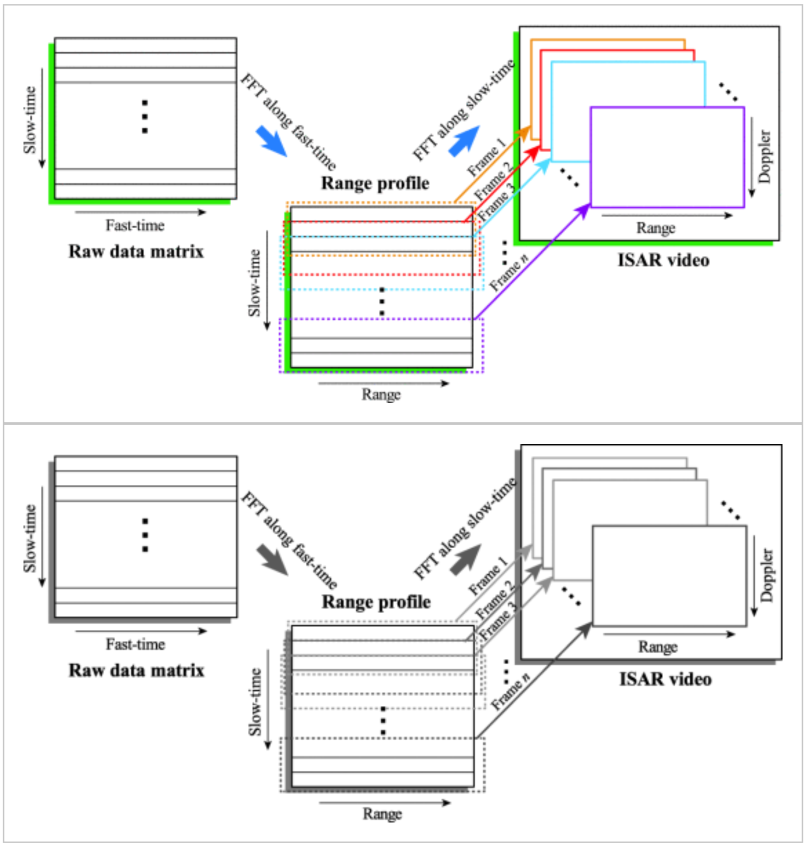

Fig. 20.
Generation of range-Doppler ISAR video based on two fast Fourier transforms to the original radar-detected signal.

An example using the 5.8-GHz portable radar is given in Fig. 21, where two human subjects walked back and forth in opposite directions in a narrow corridor. The radar-detected range-profile in a 73-s interval is shown in Fig. 21(b). Many strong vertical strips, which correspond to stationary objects, can be observed. Although the traces of the two moving human subjects are noticeable as indicated by A and B, they are much weaker than the stationary clutter (i.e., nearby objects) returns. Fig. 21(c) plots three frames of the real-time ISAR video obtained by processing the same measurement data. The range information is indicated in the x -axis and the Doppler information (corresponding to walking speed) is indicated in the y -axis. Frame 1 corresponds to the 7-s moment of the acquisition time, when subject A was walking toward the radar, while subject B was walking away from the radar. The return associated with subject A appears above the zero-Doppler strip, while subject B provides an echo below the zero-Doppler signature. In Frame 2 corresponding to the 26-s instant, subject A was close to the radar and was about to turn around with a near-zero velocity, while subject B was still walking away from the radar system. Frame 3 taken at the 64-s moment shows subject A walking back to the radar and subject B walking away from the radar. The echoes observed around the main signatures in these frames correspond to the micro-Doppler features of the human gaits, which were mainly caused by relative limb motion.

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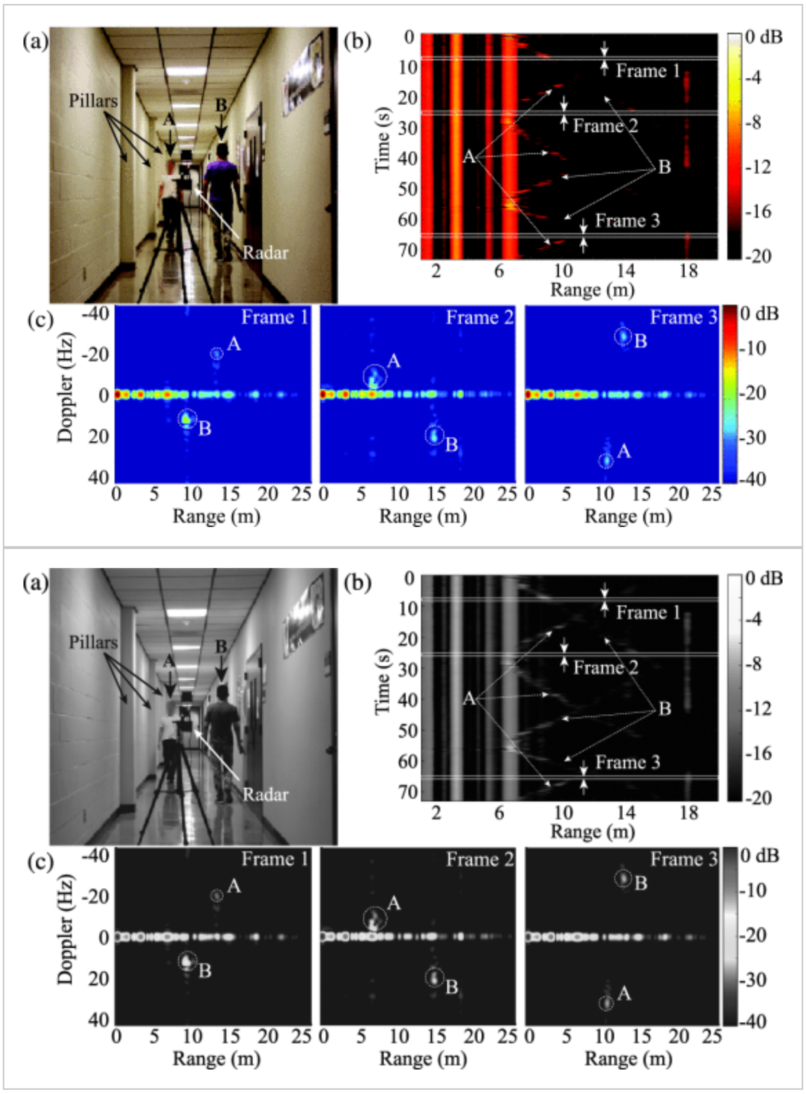
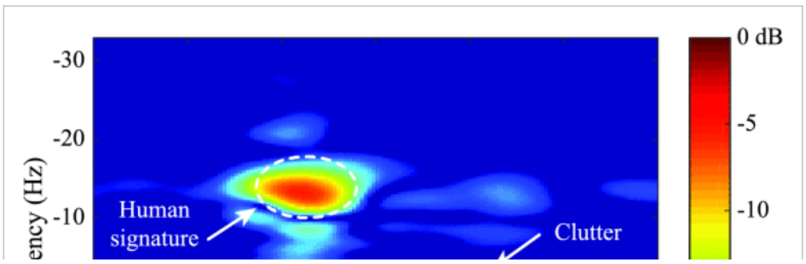


Fig. 21.
(a) Experimental setup for ISAR tracking of multiple walking subjects. (b) Range-profile matrix. (c) ISAR video frames at different moments. Adapted from [51].

It should be noted that all the stationary clutter returns in a complex indoor environment are compressed into the zero-Doppler line in an ISAR video. This leads to the advantage of easy isolation of the wanted moving targets from surrounding clutter. Furthermore, by analyzing the echoes in the ISAR image and the micro-Doppler features of human motion, gait information and fall events can be detected. An example is given in Fig. 22, where a single subject was walking with increased limb motion. It is clearly shown that the echo is defocused and more micro-Doppler features are produced. From the ISAR video, the speed, range, and radar cross section (RCS) can all be observed in real time, which provides possibility of classifying human motions and detect falling of a person. In [104], a case study was conducted to demonstrate the ability of a 5.8-GHz portable FMCW radar sensor to detect fall events and differentiate falls from other activities, such as a sudden jump based on the Doppler, range, and RCS extracted from real-time ISAR imaging.



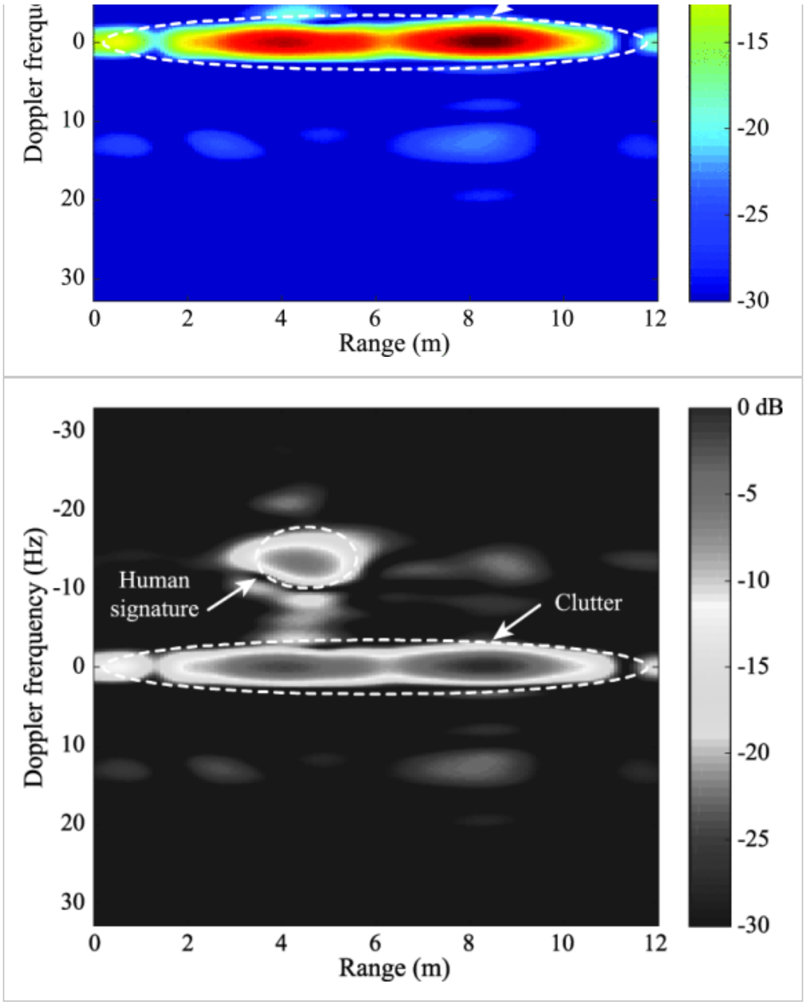


Fig. 22.
ISAR image of a walking subject with increased limb motion, which creates abundance of information due to the micro-Doppler effect.

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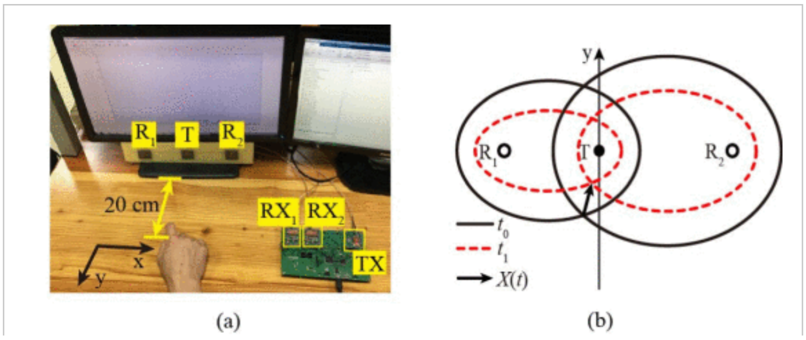
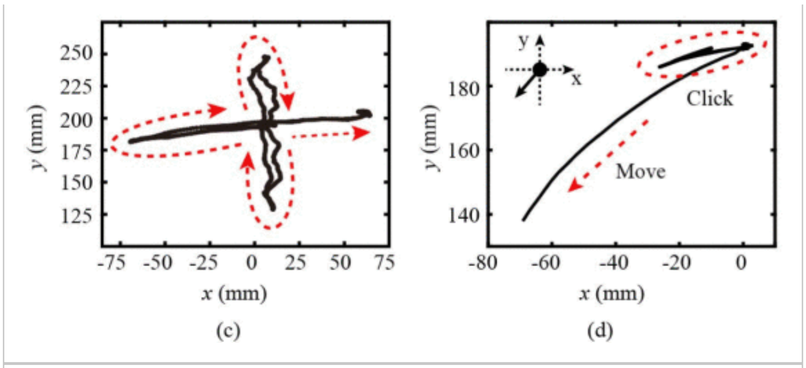
C. Hand Tracking and Gesture Recognition Using SIMO

In addition to gesture characterizations based on time–frequency analysis and "micro-Doppler" effect, linear time-domain motion tracking based on CW radar sensors can also be used in hand tracking, gesture classification, and recognition. A recent example was reported in [105] and [106], where the feasibility of human hand gesture recognition was investigated. This paper tried to realize the basic "moving" and "click" functions of a mouse by remotely tracking the hand and finger actions based on a single-input multiple-output (SIMO) Doppler radar sensor.

The experiment setup is shown in Fig. 23(a). The SIMO system consists of one transmitting and two receiving channels designed to operate at 5.8 GHz. The antennas were placed on the lower side of a computer's display to detect the hand actions in front of them. For a hand moving on the surface of the desktop, a 2-D motion tracking algorithm can be derived by locating the point intersected by the desk surface and the surfaces of two ellipsoids with focuses at the locations of the antennas, as shown in Fig. 23(b). It turned out that when the transmitting and receiving antennas were placed in a straight line parallel to the desktop, two simple equations can be derived to track the trajectory of the hand motion based on the Doppler information demodulated from the scattered signal using an arcsine algorithm. As an experimental demonstration, Fig. 23(c) and (d) shows the reconstructed cross-motion pattern and the moving-click pattern of a hand moving on the desk surface.





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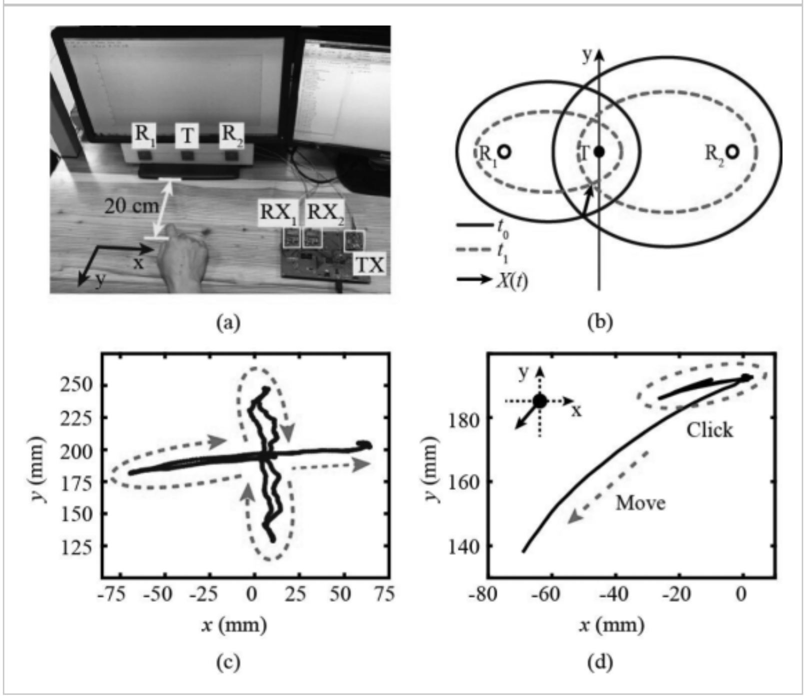

Fig. 23.
(a) Experimental setup for hand location and finger gesture tracking. (b) Geometrical interpretation of the problem. (c) Measured hand movement in the x - and y -directions. (d) Finger click measured together with hand movement. Adapted from [106].

These results imply that hand tracking and gesture recognition can be realized using a narrowband signal with the aid of multiple receivers or transmitters, providing a way of enhancing access to the limited radio spectrum.

SECTION V.
Conclusion

Driven by the need of improved applications on the areas of healthcare, automotive navigation, and smart human-computer interface, the past decade has witnessed rapid advancements in radio frequency sensing and detection technologies. This paper reviews some of the recent developments on portable CW radar systems for short-range applications that are based on sensing of motion, displacement, and location. Although lots of progress has been made by engineers and researchers to minimize radar sensors and make them "smart" for IoT applications, the adoption of radar sensors in daily civilian life is still greatly lagging behind other technologies, such as cameras and accelerometers. With radar's unique advantage of being able to see-through-the-wall and better protect privacy compared with cameras, the microwave society should be optimistic about the potential and future of portable radar sensing technology. The continued contributions from the members in the RF/microwave society will be greatly valued and appreciated.

Keywords

IEEE Keywords
Doppler radar, Radar tracking, Frequency modulation, Microwave theory and techniques, Monitoring

monitoring

INSPEC: Controlled Indexing
printed circuits, radar signal processing

INSPEC: Non-Controlled Indexing
portable short-range noncontact microwave radar system, motion detection, imaging application, positioning application, semiconductor technology, integrated circuit chip, printed circuit board, signal-to-noise ratio, range detection capability, on-board signal processing algorithm, wireless sensing application, next-generation portable smart radar system

Author Keywords
Doppler, frequency-modulated continuous wave (FMCW), interferometry, inverse synthetic aperture radar (ISAR), localization, radar, short range, time–frequency

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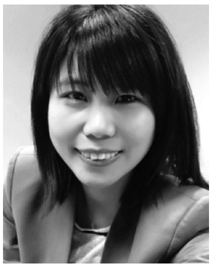

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Tzyy-Sheng Horng (S’ 88–M’ 92–SM’ 05–F’ 16) was born in Taichung, Taiwan, in 1963. He received the B.S.E.E. degree from National Taiwan University, Taipei, Taiwan, in 1985, and the M.S.E.E. and Ph.D. degrees from the University of California, Los Angeles, CA, USA, in 1990 and 1992, respectively.

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Since 2006, he has been an Associate Professor with the Department of Signal Theory and Communications, University of Alcalá, Alcalá de Henares, Madrid. He has been, for several research stays, with the C2S2 Department, XLIM Research Institute, University of Limoges, Limoges, France, the Telecommunications Institute, University of Aveiro, Aveiro, Portugal, the U.S. Naval Research Laboratory, Microwave Technology Branch, Washington, DC, USA, and Purdue University, West Lafayette, IN, USA. His current research interests include the design of fixed/tunable high-frequency filters and multiplexers in planar, hybrid, and monolithic microwave-integrated circuit technologies, multifunction circuits and systems, and software-defined radio and radar architectures for telecommunications, remote sensing, and biomedical applications.

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