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NONCONTACT VITAL SIGN DETECTION WITH UAV-BORNE RADARS

An Overview of Recent Advances

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Airborne radar carried on board unmanned aerial vehicles (UAVs) is serving as the harbinger of new remote sensing applications for security and rescue in inclement environments. The mobility and agility of UAVs, along with intelligent onboard sensors (cameras, acoustics, and radar), are more effective during the early stages of disaster response. The ability of radars to penetrate through objects and operate in low-visibility conditions enables the detection of occluded human subjects on and under debris when other sensing modalities fail. Recently, radars have been deployed on UAVs to measure minute human physiological parameters, such as respiratory and heart rates while sensing through clothing and building materials. Signal processing techniques are critical in enabling UAV-borne radars for human vital sign detection (VSD) in multiple operation modes. UAV radar interferometry provides valuable VSD in both hovering and flying motions. In the synthetic aperture radar (SAR) configuration, UAV-based VSD is available at a high spatial resolution. Novel radar configurations, such as in through-material sensing, UAV swarm, and tethered UAVs, are required to penetrate obstacles, facilitate multitasking, and allow for high endurance, respectively. This article provides an overview of the recent advances in UAV-borne VSD, with a focus on the deployment modes and processing methods.

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Introduction

UAVs, also referred to as *drones*, are emerging as valuable tools for surveillance, medical assistance, consumer goods delivery, and policing [1]. In particular, commercial drones are now deployed for disaster response, including damage assessment, map updates, and search-and-rescue operations (SROs) for stranded victims [2]. In this article, we focus on the latter application of UAV-based physiological VSD of victims.

When considering emergency response in a crisis, early determination of the location and status of victims is paramount. In this context, drones exhibit enhanced mobility, accessibility, agility, and height advantages over humans, animals, and robots on the ground. A UAV is more efficient and less error prone than human rescue teams and trained service dogs in extreme environments, with shortage of time, and under difficult physical conditions. Compared to ground robots, UAVs do not require invasive equipment, and their mobility is not considerably challenged in off-road and complex terrains with mudslides, avalanches, and flooding.

The performance of SRO UAVs is significantly improved by equipping them with intelligent sensors that are powered by computer vision and machine learning techniques. These sensors comprise specialized optical devices in addition to sensors for flight control, stabilization, and communications. The optical sensors are task specific and cater to functions such as super high-resolution (SHR) red, green, blue (RGB) cameras for detailed vision inspection during daytime; infrared (IR) thermal cameras for creating a pseudocolor heat map of the scene from temperature measurements; and time-of-flight distance sensors (depth sensors or lidar). In most cases, fusing measurements from the depth sensors and vision cameras provides an accurate 3D map.

The aforementioned noncontact sensors are also suitable for measuring physiological signs of any living human on the ground from a UAV platform (Figure 1). Although camera systems are favorable for line-of-sight (LoS) object detection and lidar systems come with high spatial resolution, these sensing modalities are limited by debris and building materials that cover or occlude the victim at the disaster site. On the other hand, microwave signals at appropriate radar frequencies not only penetrate through such obstacles but also perform well in unfavorable conditions, such as harsh weather and low visibility. In this article, we focus on radar-based VSD from UAV platforms.

UAV-Based VSD: State of the Art

A radar transmitter emits a periodic train of known narrow-band pulses that interact with a human subject. The resulting reflections from the subject are received by the radar as superimposed, attenuated, time-shifted, and frequency-modulated (or Doppler-shifted) replicas of the transmit signal. The time delay and frequency modulation in the received signal are directly proportional to the unknown range and velocity of the target, respectively. By estimating these unknown parameters of the received signal, the radar determines the physiological parameters, such as the respiratory and heart rates, of the human subject.

The radar and optical frequencies, including those of visible and invisible light, occupy distinct positions in the electromagnetic spectrum. Whereas the radar carrier wavelength for UAV VSD applications ranges from fractions of a meter to a few millimeters, optical wavelengths range from approximately 380 nm to 1 mm. As a

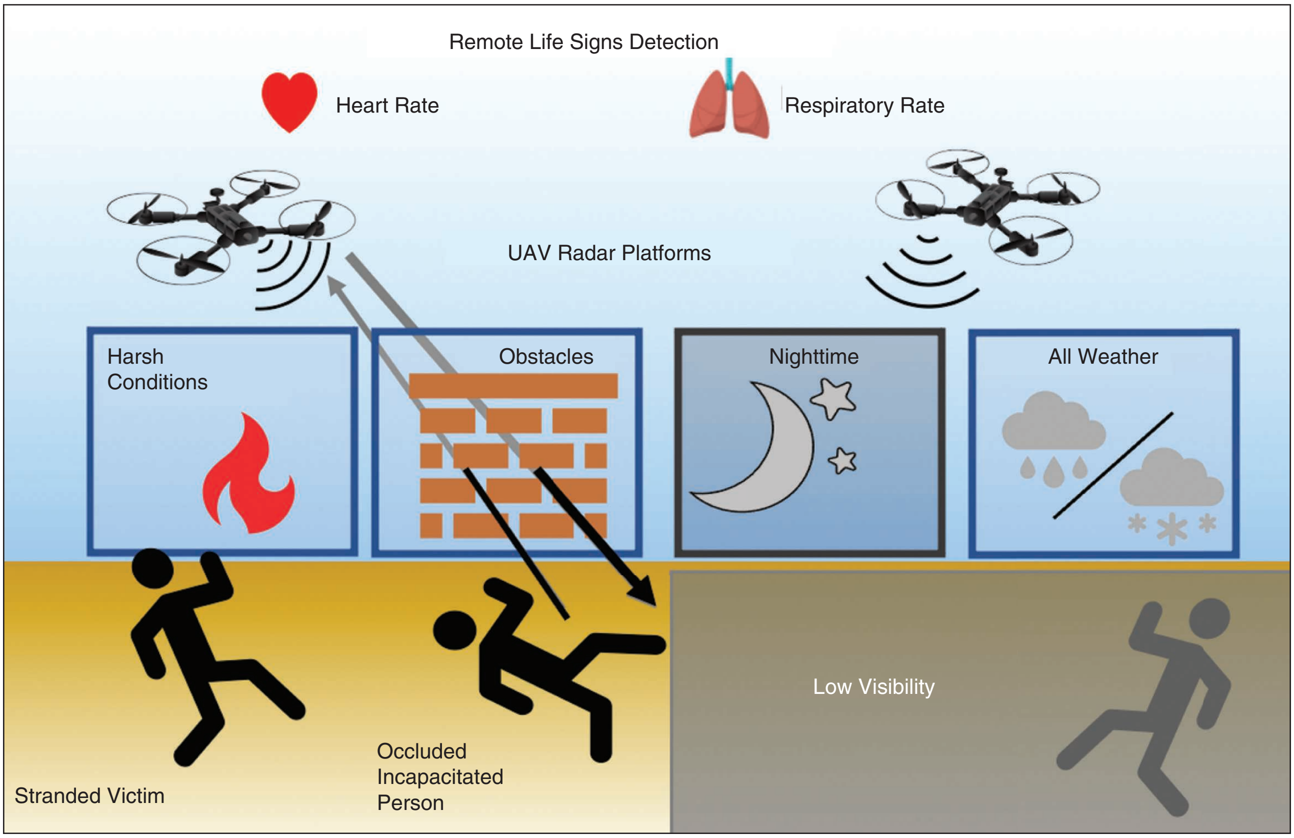


FIGURE 1 A radar mounted on a UAV (or UAV swarm) detects living humans on the ground by extracting their vital physiological measurements from the received echoes. Unlike optical systems, radar signals leverage see-through capability at the microwave level in harsh weather and low-visibility conditions or when the victims are covered by debris.

result, the physiological phenomenology and hardware differ considerably for radar and optical sensors. In the case of radar, the received signal containing the human physiological signature exhibits the micro-Doppler effect [3] arising from the micromotions of body parts such as the lungs and the heart; for example, breathing results in the displacement of a few millimeters and heartbeats in that of much less than a millimeter. The phase of the received signal is sensitive to these tiny motions, and the extraction of the Doppler shift embedded in the phase provides a good estimation of the vital signs.

Smaller wavelengths (or higher frequencies) yield better phase sensitivity but do so at the cost of shorter sensing distances and lower-penetration capability. This system design tradeoff must be considered when employing UAV radars for VSD. Table 1 summarizes these differences among the radar and optical approaches, as reported in the major prior works on UAV-based VSD. In [4] and [5], RGB cameras were deployed on UAVs, but the system could function only in the hovering mode. To aid vision during nighttime, the hovering UAV in [6] used an IR sensor, but the subject was marine life. A UAV-borne frequency-modulated continuous-wave radar was recently employed in [7], using an ideal straight-line route. An ultrawideband (UWB) radar on the hovering quadcopter in [8] was able to provide accurate VSD.

Stand-alone, small-scale radars have been available for measuring the breathing and heart rates of humans based on the Doppler effect since the 1970s. This was followed by advancements in signal processing techniques, hardware, and antenna designs that enabled radar as a potential noncontact remote sensing technology for health monitoring. Recently, through-wall multiple heartbeats detection was demonstrated using wideband radar [9].

Another widely used noncontact VSD technique is remote imaging photoplethysmography (RIPPG) [10]. Instead of exploiting the Doppler effect of moving body parts, as in radars, the RIPPG employs optics to detect minute color shifts caused by blood circulation in the exposed skin of facial areas, hands, and feet to estimate the vital signs. This variation in the radiant intensity of human skin with pulses of blood and motions is not discernible to the human eye but is easily captured in a sequence of video frames. However, RIPPG is not robust against the dynamic changes in visibility conditions and skin tones.

The other related techniques include IR thermography, which extracts breathing signatures by evaluating the temperature changes of the human nostril [6]. Depth sensors have also been used to directly measure the physical displacement of the chest to estimate breathing

TABLE 1 ***A summary of the state of the art in UAV-based noncontact VSD.***

Sensing Devices	*Principle*	*Drone Motion*	*Output*	*Subject*	*Advantages*	*Drawbacks*	**Range (m)*
RGB camera [4]	Photoplethysmography	Hovering	Heart rate	Human	Excellent vision in daytime	Need for visible skin, unable to penetrate barriers, and privacy issues depending on the use cases	~3
RGB camera [5]	Motion	Hovering	Respiratory rate	Human	Excellent vision and long detection range	Unable to penetrate barriers and privacy issues	~3
IR thermal camera [6]	Temperature	Hovering	Respiratory rate	Whale	Night vision	Unable to penetrate barriers and minor privacy issues	~20
FMCW and CW hybrid radar [7]	Micro-Doppler	Flying in a straight path	Respiratory rate	Human	Through-material sensing, all weather, and able to localize without vision sensors	Sensitive to platform motion and a long acquisition time	~4
UWB impulse radar [8]	Micro-Doppler	Hovering	Respiratory and heart rates	Human	Through-material sensing and all weather	Sensitive to platform motion	~3

FMCW: frequency-modulated continuous wave; CW: continuous wave; UWB: ultrawideband.
*For cameras, the range is enhanced to a few hundred meters with the aid of zoom lenses. For radars, the range is extended by a few hundred meters with higher transmit power and antenna directivity.

rate. In general, this outperforms the efforts to extract chest motion by tracking image-pixel value change [11]. Nearly all of these other sensors are incapable of penetration through obstacles in disaster areas. This makes radar very attractive and beneficial for UAV-based VSD.

In practice, a successful disaster response and SRO involves path planning, resource allocation, human localization, and life signs detection; each of these tasks is accomplished using multiple sensing modalities. UAV radar measurements usually complement the high-resolution information obtained from vision sensors. In [13], a UAV-based communications sensor was used as a mobile base station to enhance the coverage and capacity of cellular networks. It leveraged the inherent relocation flexibility of the drone, which resulted in a higher probability of establishing an LoS link with the ground mobile users. To accurately detect open-water swimmers, UAV-based video identification has been used. In the context of cetacean conservation, Horton et al. [6] proposed UAV IR thermography for monitoring the vital signs of free-ranging whales. UAV radar-based VSD is a relatively new area, and, hereafter, we focus on the design and processing aspects of this technique only.

Design and Prototypes

Most commercial drones have a layered organization of hardware modules (Figure 2). Connected to the physical-layer sensors is the network layer with medium access control, which provides network connectivity to all the other modules. Within the same layer is the communications sublayer, which comprises radio management for power control and optimization of communications with other drones within reach; a self-organizing network module for exchanging messages and coordinating with nearby drones; and information relay, for receiving data from other drones and forwarding these data to the next drone or broadcasting them until its and other drones' destinations are available.

Connected to all of the layers is a cognitive module that provides generic artificial intelligence algorithms to help with the decision making. A UAV control layer is responsible for the motion and routing. Its mobility management module performs path planning while also considering the objectives and probable actions of neighboring drones. This plan is then implemented by a separate navigation and flying control module. The layer also has energy management to keep track of the remaining battery power.

The application layer is task specific and dependent on the available sensors. For the LoS scenario, VSD involves a fusion of vision and radar information. The color/IR cameras are first used to identify the contours and body features of a possible human subject through computer vision algorithms. Then, the region of interest (chest area) is identified, and, through a vision-aided mechanical/electronic steering, the radar beam illuminates the chest for vital sign extraction. Note that the radar- and vision-based biometric data are used together for cross validation and sensor fusion to enhance the robustness of measurements. However, in a non-LoS situation such as an obstructed victim, only the penetrating signals from a radar are useful. The UAV uses an onboard communications system to identify the hotspot areas where victims might be stranded. For example, this is helpful in identifying subjects with mobile phones. Even though such victims may not be able to make a call because of injury or a breakdown in communications infrastructure, it is possible to use mobile GPS and handshake signals to locate them. Then, a UAV scans the focused area using a radar and detects living humans based on valid micro-Doppler signatures.

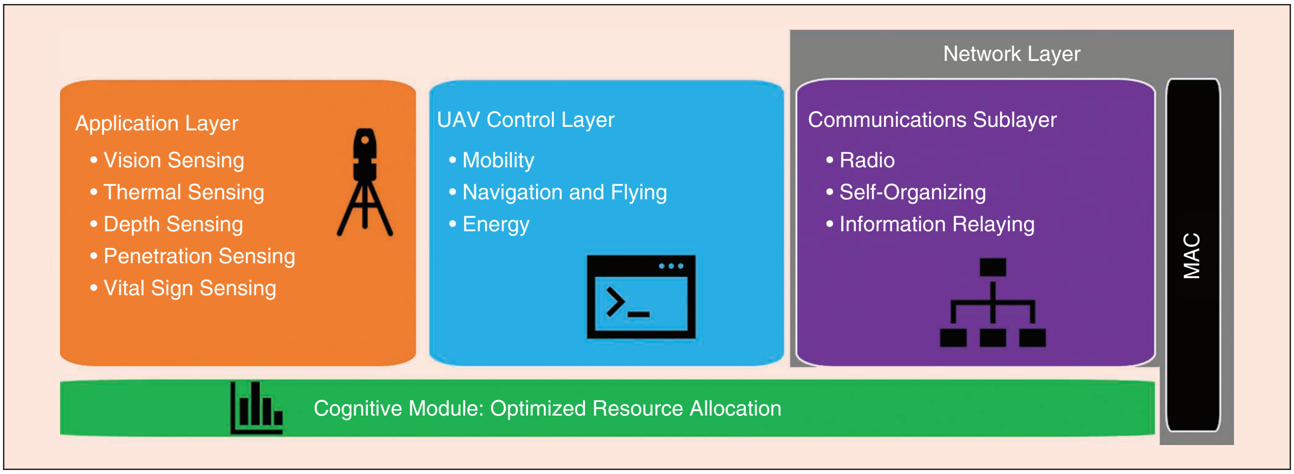


FIGURE 2 The layered organization of modules for the VSD UAV systems modified from [12], including the application layer for autonomously coordinating tasks, control layer for self-navigation and flying, network layer for communications and connectivity, and cognitive module for decision making and resource allocation across layers. MAC: media access control.

Design Considerations

The installation of a radar on board a UAV should be such that it does not hinder the common functions of the platform. Specific to VSD, the following factors determine the design.

Loading Capability

The *payload* is the weight that a drone carries. The greater payload a drone takes, the more flexible it is to supplement the system with extra cameras, sensors, packages for delivery, and additional technology to adapt to specific needs. However, the flight time is reduced when carrying more weight because the extra power required drains the battery sooner.

Flight Time

Longer flight times are required for extensively surveying a given area. Further, emergency situations typically require the frequent monitoring of sites. The drone's limited battery power constrains flight times to usually less than 1 h in many commercial UAVs. The overall design of the drone also affects the flying duration; for instance, Parrot Disco is capable of a continuous flight time of 45 min, but a similarly weighted drone, Da-Jiang Innovations (DJI) Mavic Pro, operates continuously for only 30 min. The fixed-wing, single-rotary blade in the former is aerodynamically better (less thrust) than the multirotor quadcopter design of the latter.

Radar Placement

Its small size and limited battery exacerbate the sensor placement issues in a UAV. Usually, an optical flow camera is installed on the nose of the drone for unobstructed field of view. The same applies to the installation of radar sensors, which should also not interfere with the existing cameras and sensors. An alternative deployment location is the underbelly of the drone. But it should not block the view of ultrasound sensor that is normally located under the belly, vertically facing down for determining the height from the ground and detecting the objects directly underneath the drone. The top of the drone usually has an altimeter, a nine-axis inertial measurement unit (IMU), and a GPS in protective casings. These do not compete with the radar for deployment location.

Platform Motion Compensation

Drone-based sensing systems should be able to handle motion noise during flight and still provide precise measurements for applications like aerial surveying, radar imaging, and human physiological signal measurements. There are also perturbations in platform motion while hovering. Strategically, platform motion is mitigated by mechanical stabilization, correction using digital signal processing, and sensor fusion. For example, a drone-based, forward-looking IR imaging solution combines a high-resolution radiometric thermal imager and 4,000-resolution RGB camera to create accurate orthomosaics. Similarly, a lidar and RGB solution from DJI for aerial surveys integrates a Livox lidar, a high-accuracy IMU, and a color camera. Radar sensors may also be likewise integrated with cameras. Further, using an IMU and real-time kinematic GPS, a radar-vision coupled multimodality payload is installed on the gimbals of drones for emergency response, highly accurate 3D mapping, and VSD in complex environments.

Operating Frequency

At present, the S and X bands below 10 GHz are the frequencies of choice for UAV radar VSDs. At the X band, the interference from coexisting communications is currently not a major concern. However, several LTE wireless standards, including Wide-Band Code Division Multiplexing Access, Worldwide Interoperability for Microwave Access, Global System for Mobile, Enhanced Data Rates for GSM Evolution, and IEEE 802.11b/g/n (2.4 GHz), operate within the S band. This could lead to interference with the UAV sensing transmissions. Similarly, frequencies above 10 GHz, such as millimeter-wave (mm-wave), are also being investigated for UAV radars because they offer improved resolution and a smaller hardware footprint; however, they also suffer from communications interference. This problem could be addressed using recent advances in designing and operating with a joint radar communications waveform. For example, the IEEE 802.11ad Wi-Fi preamble at 60 GHz is one of the preferred millimeter waveforms that perform both sensing and communications functions. At the mm-wave level, a more serious problem is severe attenuation and propagation losses. This makes mm-waves inappropriate for VSD because signals at such a high frequency are either unable to penetrate barriers or could be used for very short ranges.

Customized Prototypes

The Center for Wireless Information Systems and Computational Architectures (WISCA) at Arizona State University developed two UAV radar-demonstration platforms (Figure 3) assembled from off-the-shelf hardware components for demonstrating the proof of concept of UAV-based radar VSD. The flying carriers were the DJI Phantom 4 Pro and DJI Spreadwing 1000+. The former is a 3-lb quadcopter with a 35-cm diagonal length, a flight time of 30 min, and 3-lb payload-lift capability. The latter is a larger octocopter, 10 lb in weight and 104.5 cm in diagonal length, with a 20-min flight time and 11 lb of lifting capability. The installed radar system consists of a UWB impulse radar system on chip, a Raspberry Pi single-board computer (SBC) for controlling the radar and communicating with the ground PC, and power sources for the radar and the SBC. In the next section, although we discuss the common deployment modes, we include demonstrations of human VSD using these prototypes. These experiments were performed outdoors in Phoenix, Arizona, and followed governmental regulatory requirements.

Deployment Modes

The deployment configuration is critical to the quality of VSD with UAV-borne radars. The common processing modes employ radar interferometry, SAR, and through-material sensing. We differentiate these UAV radar methods by not only radar signal processing but also UAV maneuvers during the radar-scanning period.

Interferometry Mode

The interferometry mode implies that only micro-Doppler information is used in the radar processing. This mode distinguishes humans from other nonliving objects by strategically flying the UAV over certain flying routes. As the distance between the radar and the target constantly changes, periodic chest motion vibrations are extracted via micro-Doppler processing by combining data from all the range profiles. The common flight maneuvers include a linear straight path at a constant altitude, a circular path centered on the human target at a constant altitude, and approaching the human target while changing only the height of the drone. Note that many commercial drones allow users to preprogram the flying route for a more precise flying experience. For instance, DJI software features a waypoints function, which allows for customization of the flying path, distance (as small as a few meters), and speed.

Some representative interferometry results from the WISCA prototypes are shown in Figure 4. When the drone hovers right above the human chest area at close distances [Figure 4(a)], both the breathing and heartbeat signatures are easily identified. More specifically, breathing signal variations are retrieved, and the heart rate is estimated during this period. When the drone moves strategically around the target [Figure 4(b)], the resulting measurement is noisy, but a discernible micro-Doppler signature from regular chest vibration is still observed in spectral analyses.

Vital-SAR Imaging

In the SAR mode, the radar employs an antenna array on the drone to image the targets through several measurements while the flight's movement continues.

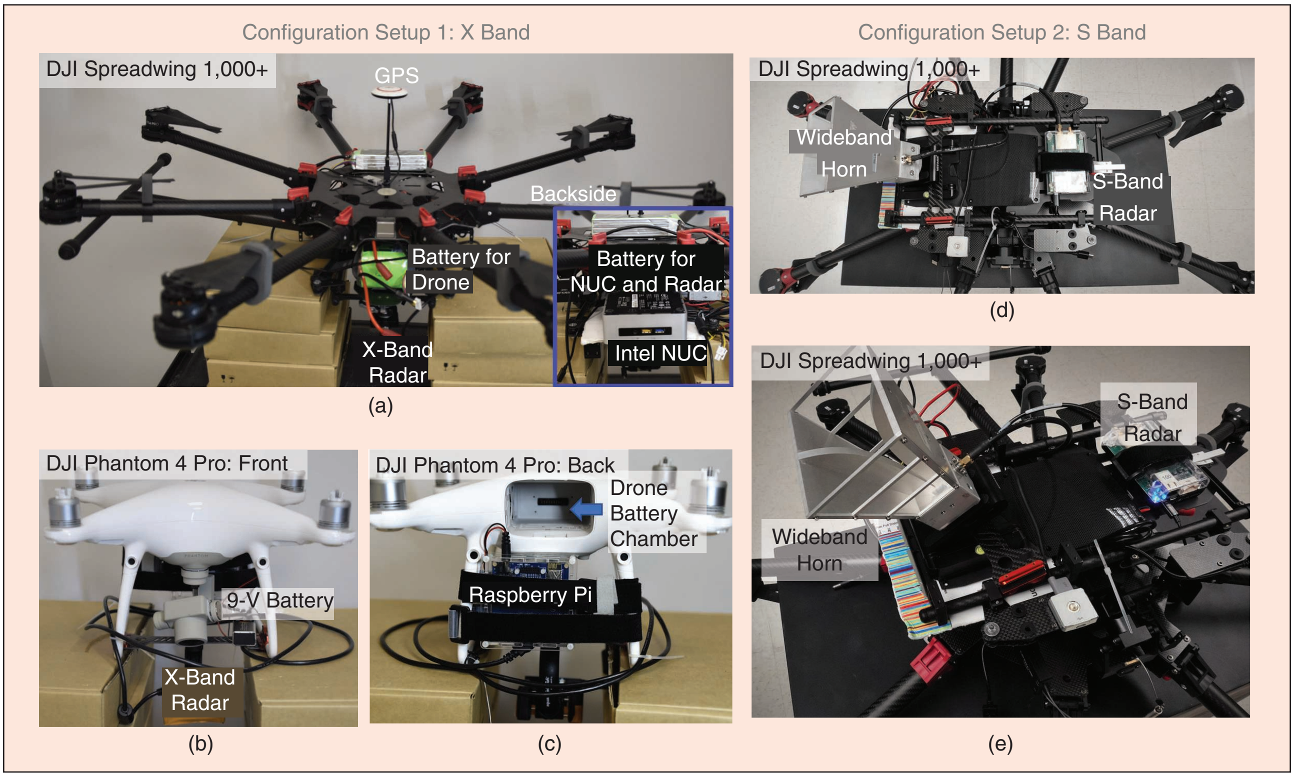


FIGURE 3 Arizona State University UAV radar-demonstration platforms. In configuration 1, near-range and LoS scenarios are sensed using an X-band radar installed beneath two different types of flying carriers. (a) The DJI Spreadwing 1000+ (octocopter) employs Raspberry Pi. (b) The front and (c) back views of a DJI Phantom 4 Pro (quadcopter), which uses an Intel next unit of computing mini PC. Configuration 2 for non-LoS sensing requires more power but offers deep penetration and a longer range. Here, an S-band radar with a wideband directional horn is installed beneath the larger-carrier DJI Spreadwing 1000+ with approximately 10 lb of loading capability. The horn is securely mounted on a customized z-shape flex tilt head connected the belly of the DJI Spreadwing 1000+. (d) The top view of the radar's placement at the bottom of the DJI Spreadwing 1000+ and (e) the side view of the radar's placement.

This synthesizes a larger antenna aperture to achieve a finer spatial resolution than what would be possible with the limited aperture of the onboard antenna. The SAR processing generates an intensity map image that indicates the location of strong scatterers. In [7], SAR-based VSD, or vital-SAR, imaging was introduced. Here, SAR processing is combined with VSD to distinguish living humans from static clutter in the reconstructed SAR image. The SAR image formation and vital sign extraction themselves were accomplished separately by flying the drone twice over the same path.

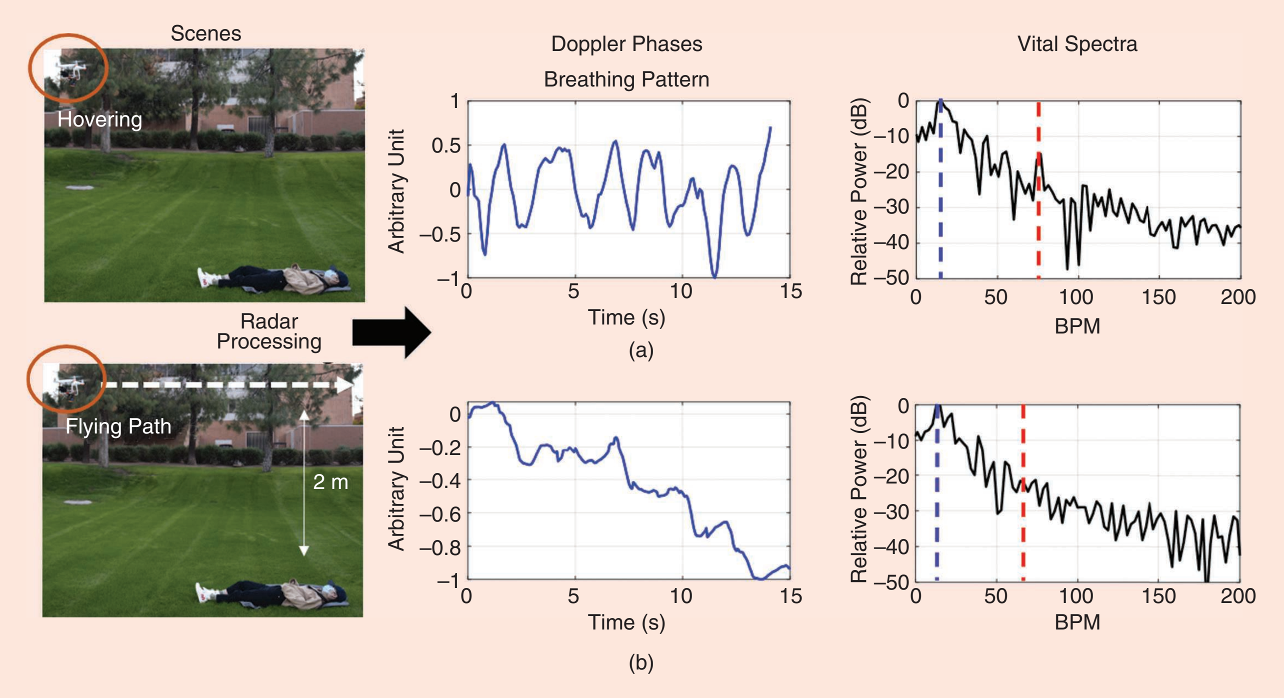
The WISCA prototypes improve on the work of Yan et al. [7] by performing vital-SAR imaging in a single flying path and without using vision sensors. Configuration setup 1 [see Figure 3(a)–(c)] comprises an X-band UWB impulse radar with a 1.5-GHz bandwidth installed at the bottom of the drone. During the flight, the radar always points in a downward direction perpendicular to the straight flight path and forms a side-looking SAR. Note that, compared to the SHR camera, a radar SAR image provides limited and abstract vision content. But SAR clearly outperforms SHR in harsh weather, with obstructions, and in low-visibility conditions. Figure 5(a) shows an example of vital-SAR imaging with a WISCA prototype. After raw data [Figure 5(b)] are focused, the resulting SAR image [Figure 5(c)] shows two strong energy clusters corresponding to a corner reflector and a human subject in the RGB image of the scene. Then, the time-frequency representation [Figure 5(d)] of the breathing signals distinguishes the living human subject from the corner reflector.

Through-Material Sensing

As mentioned earlier, through-material imaging is the major advantage of using radar over optical sensors. Configuration setup 2 [see Figure 3(d) and (e)] comprises an S-band UWB impulse radar with a 1.5-GHz bandwidth and a wideband directional horn installed at the bottom of the drone. Figure 6 displays two examples of WISCA UAV radar in detecting the vital signs and activity of an obstructed subject. In the first example, Figure 6(a), the breathing pattern is recovered when the human subject is covered by bedding material; for a radar, such an obstruction causes insignificant signal attenuation. In the second scenario, Figure 6(b), the UAV-borne radar detects a human walking activity (5–12 s) and extracts a stationary VSD signature after PMC [8] (13–20 s) through a wall. Note that the locations of wall reflections slowly drift over time because of the hovering UAV platform.

Practical Considerations

There are various practical and performance issues to consider in a UAV radar VSD problem. The performance metrics for radar-based VSD are not very well defined and change as per the specific application. Novel strategies for route planning, time on target, and computational offloading are required to adapt to the limited shelf life



(a)

(b)

FIGURE 4 UAV-borne radar interferometry examples using two flight maneuvers: (a) hovering and (b) flying in a straight path. The UAV is enclosed within a brown circle. The breathing signals are detected in both cases; however, heartbeats are detected only during hovering. The dashed blue and red lines denote the breathing and heartbeat references. BPM: beats per minute.

of a drone's battery and the thinned computational resources available on a UAV processor.

Performance Evaluation

Prior works define the probability of detection for VSD in different ways. The radar VSD's performance should be validated before deployment. In the case of breathing activity, one intuitive definition is that the percentage of duration the radar estimates of breathing rate has an accuracy of 1 beat per minute for a 5-min measurement, wherein the moving window processing is performed every 15 s in 1-s increments. The rate is then estimated from spectral peak detection in the desired portion of the echo spectrum, and an empirical cumulative

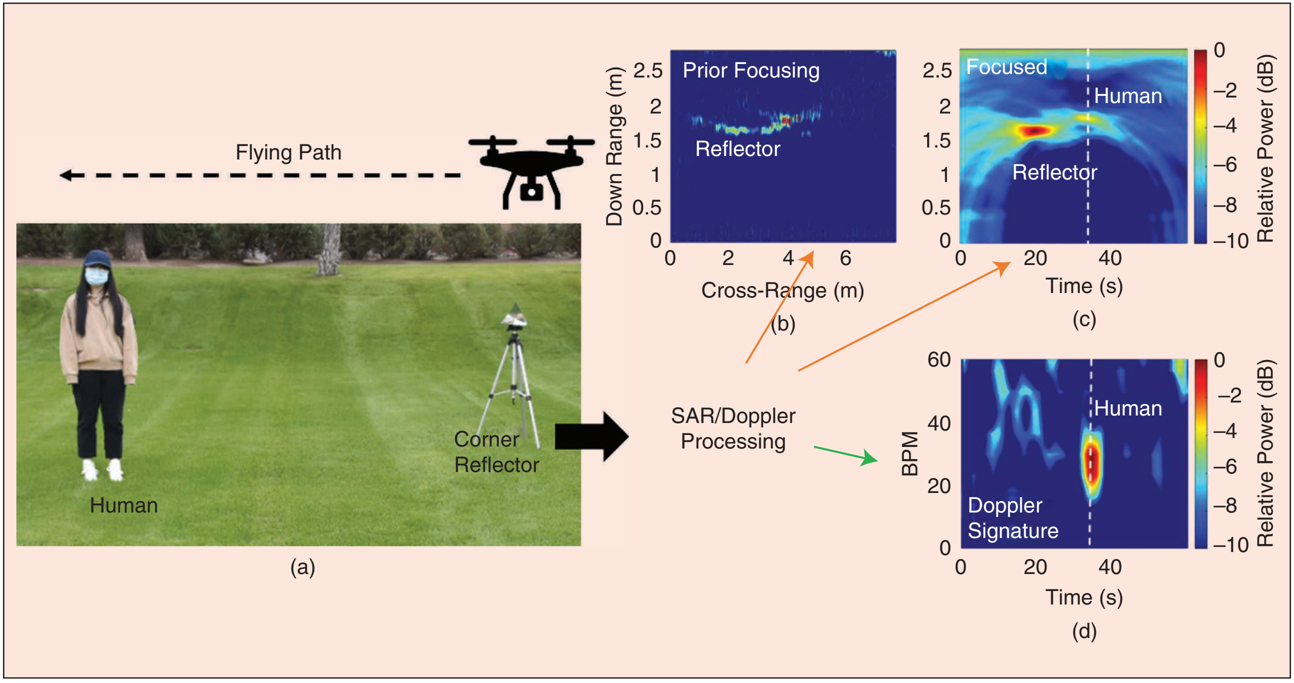


FIGURE 5 Vital-SAR imaging. (a) An RGB image of the scene shows a corner reflector and a human subject on the scene scanned by the UAV flying from right to left. When the (b) raw signal from SAR is (c) focused, only the locations of both targets are revealed. (d) The VSD processing then identifies the human micro-Doppler (breathing). BPM: beats per minute.

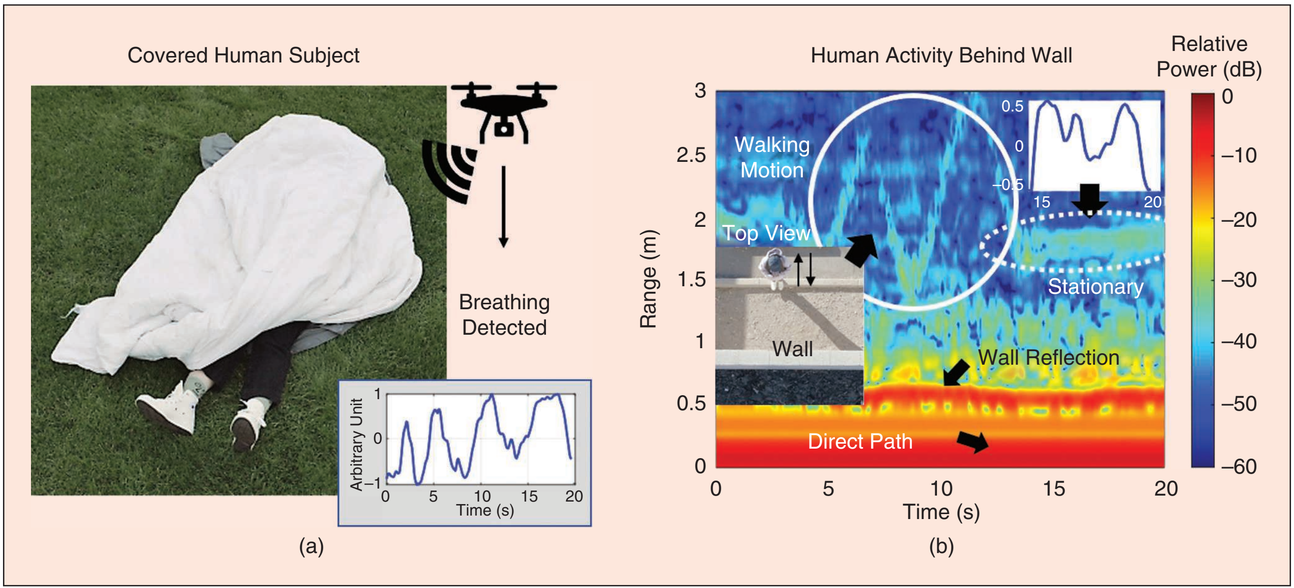


FIGURE 6 Through-material imaging for VSD. (a) The UAV radar extracts the breathing pattern (inset) of a human subject covered with bedding. (b) The same radar performs the through-wall imaging of a walking human (left inset), whose trace is enclosed by the white circle. For 13–20 s, when the subject is stationary, the radar is able to extract the behind-the-wall VSD signature of chest motions after PMC [8].

distribution function of breathing rate estimation error is obtained to compute the detection probability.

Path Planning

The limited battery power implies that the drone remains in the air for a shorter time. As a result, in UAV communications research, planning and finding an optimal route of the drone have been extensively investigated to obtain an optimal route. Here the objective is to enhance the data rates and serve as many users as possible. However, in a UAV radar VSD application, usually an exhaustive search path is required to locate stranded human subjects. A suitable path planning to cover the entire area of interest in the shortest duration may be explored to maximize the use of the available battery power.

Dwell Time

A quick identification of living forms means timely SROs for stranded victims. In general, the dwell time (or time on target) of a UAV radar to obtain reasonable VSD estimates depends on the sensing operation mode, scanning-area size, auxiliary sensor availability, computational power, and prior site information. For example, the interferometry mode is generally faster than computationally expensive SAR imaging. If vision sensors are available, they may be used to aid the beam alignment of the radar. Otherwise, diligent scans are needed to identify regions of interest. In the experiments mentioned in this article, the dwell time was at least 15 s.

Multiple Targets

VSD becomes increasingly challenging when multiple objects are present. If the interfering object is a stationary nonhuman subject, then it is easy to differentiate it from human vital sign motions. The stationary object occupies the lower-Doppler spectrum, distinct from the high-VSD Doppler. If the received echoes comprise multiple stationary human subjects, they are separated at the receiver using range or angular differences. However, when there are multiple moving humans in the target scene, then, after platform-motion compensation, techniques such as joint probabilistic data-association filters and multivariate variational mode-decomposition are employed to distinguish the VSD echoes emanating from different subjects [14].

Offloading and Edge Computing

Whereas the data collection and storage in drone-based sensing are performed in real time in the field, the data processing is carried out offline on another computer to save on flying/hovering duration and battery power. Some drones may not even be equipped with heavy computational resources; however, offline processing decreases the update rate and is not adaptive. Recently, the application of edge computing (EC) has gained much attention in drone-based sensing. EC pushes computational resources from the data center to the edge of the network to reduce computational latency and enhance real-time and adaptive data acquisition. The EC-enabled UAV is accompanied by a nearby server for a low-latency data exchange. It may also offload some computationally expensive VSD tasks to an EC server.

Challenges and Future Directions

Large coverage, quick response, constant monitoring, and precise surveying are major challenges for deploying UAVs in disaster response and similar situations for VSD. Although the focus of this article is on radar processing, design, and deployment, several other important aspects are also currently under investigation. These include new regulatory policies, data integrity, privacy concerns, and the reliability of UAVs with respect to accidents or malicious risks. Some emerging applications and considerations of UAV radar VSD are discussed in the following sections.

VSD With UAV Swarms

For quick coverage of a large area, a swarm of multiple UAVs is capable of coordinated scanning. A heterogeneous swarm with different types of drones provides a multitasking ability to perform various missions, such as providing temporary communications service, disaster site mapping, SRO, and medical material delivery. Each of these activities requires specific competences, thus necessitating more than one type of drone and numerous pieces of sensor equipment. Multiple drones also perform collaboratively, with computationally efficient inter-UAV offloading strategies, to accomplish a single task with greater efficiency and improved performance. For example, in [15], a distributed UAV radar array is investigated to provide a desired beampattern for communications and sensing. Such coordinated UAV swarm signal processing is critical for improving the current estimates of vital signs obtained via a single drone.

VSD With Tethered Airborne Sensing Platforms

The short flights and service times of most commercially available UAVs determine the need to frequently recharge. This temporarily leaves UAVs out of service. Besides attempts to develop new propulsion technology and improve drone aerodynamic design, efficient communications, onboard processing, and solar-powered UAVs, the emerging technology of tethered UAVs (tUAVs) addresses the limitations in flight times. tUAVs are continuously powered and have been proposed to establish a reliable/efficient backhaul link to the ground station for data transfer and communications services [13]. These multipurpose tUAV platforms are feasible for long-term VSD services.

VSD With Signal-of-Opportunity PMC

In the absence of wind, the measured platform motion of UAVs in hovering state is usually of the order of a few centimeters. This perturbation in motion is significantly larger than a typical physical displacement of chest motion and heartbeats. The PMC techniques discussed in the "Design Considerations" section exploited mechanical cancellation and sensor fusion. When such methods are unavailable, differential detection using opportunistic signals may be used in through-wall VSD from a hovering UAV. Assuming that the radar emits wideband signals, the reflections from the wall and the human subjects are separated in the range profile. The backscattered energy from the wall contains only the platform motion while that from the human has both the platform motion and vital signs. Through advanced signal processing of mixing the two signals, the VSD signal is obtained using correction for the platform motion.

tUAVs ARE CONTINUOUSLY POWERED AND HAVE BEEN PROPOSED TO ESTABLISH A RELIABLE/EFFICIENT BACKHAUL LINK TO THE GROUND STATION FOR DATA TRANSFER AND COMMUNICATIONS SERVICES.

UAV VSD for Pandemic Mitigation

Remote sensing UAVs with multisensor modality are useful as telemedicine platforms. In a pandemic situation, such as COVID-19, UAV radars equip front-line medical professionals to perform their job with appropriate social distancing guidelines and minimal contact. A highly autonomous UAV installed with a thermal imager, RGB depth camera, and radar sensor is capable of providing remote data collection and the monitoring of patients in quarantine [see Figure 7(a)–(c)]. Health-care workers and medical professionals need data to manage a rapidly spreading respiratory pandemic. This UAV architecture is suitable for extensive instrumentation in Internet of Things connectivity, where it communicates with and acquires patient information from a wearable sensor network. In real time, this aids in efficiently covering a large area in a short period of time for sanitization,

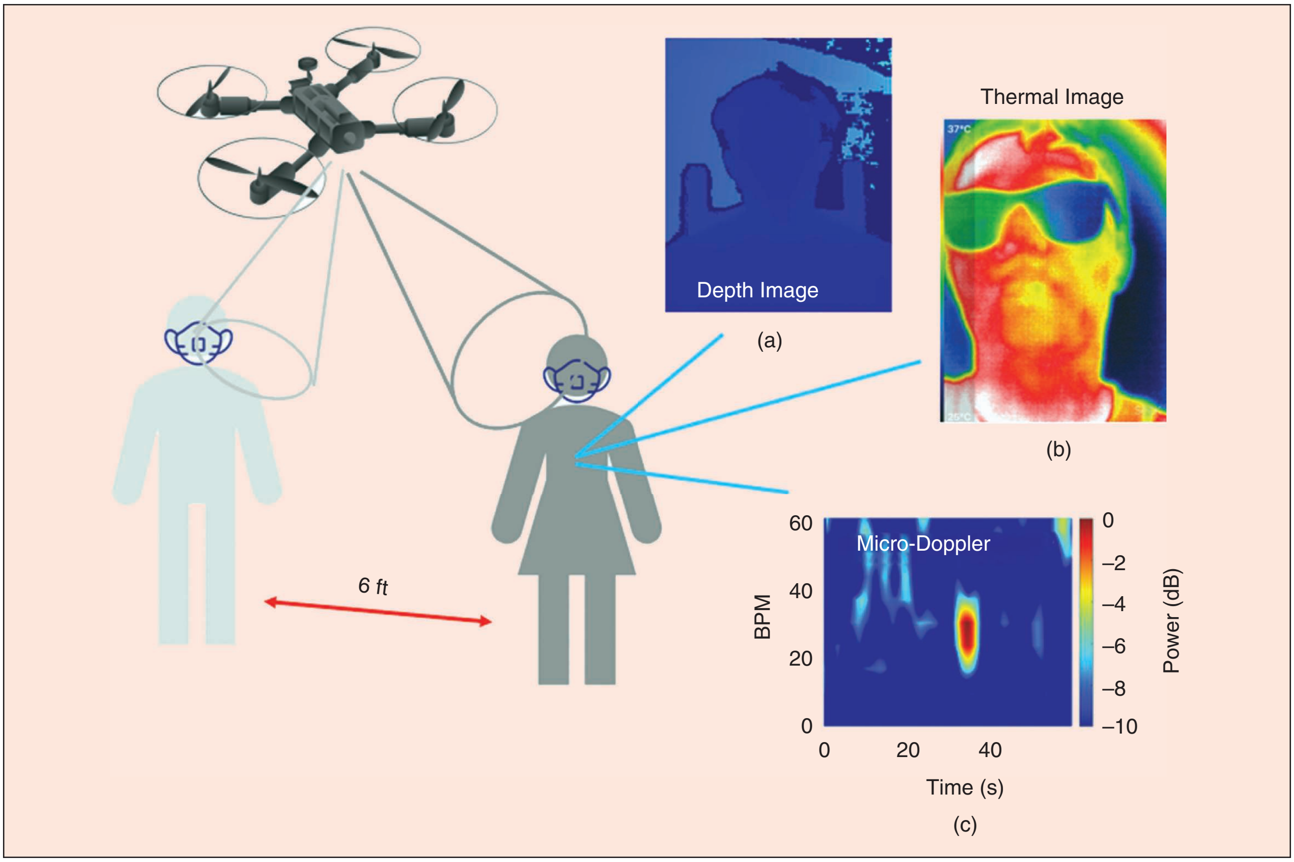


FIGURE 7 The various VSD sensors installed on UAVs aid in patient monitoring during pandemics such as COVID-19. (a) Coupled with RGB images, the depth sensors provide remote 3D information about adherence to social distancing. (b) Thermal sensors dispense body temperature images through a noncontact interaction with the patient. (c) UAV radars with suitable PMC yield useful vital sign measurements without causing any discomfort to the subjects.

thermal image collection, and patient monitoring without increasing the risks of the viral exposure to medical professionals.

Conclusions

UAV radar VSD sensing complements the information obtained from existing cameras/sensors. Radar interferometry is the simplest LoS deployment mode that operates in both hovering and flying motions. It extracts micro-Doppler activity of body parts to estimate vital signs through repeated scans of the subject. In the non-LoS case, the UAV radar employs through-material and beyond-a-wall image processing to extract VSD of occluded subjects by filtering out the embedded clutter signals. In the case of strong static clutter, the exploitation of platform motion to mimic SAR imaging is helpful in reasonably extracting VSD. Future directions include VSD with UAV swarms and tUAVs, developing advanced PMC techniques, and investigation for telemedicine during a pandemic.

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