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Opportunities and Challenges for Radar Sensing For Pandemics: COVID-19

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ABSTRACT

Non-contact sensing using radar technologies is a prospective technology in combating pandemic diseases such as the COVID-19. Current literature shows the capability of radar for cardiopulmonary signs detection and for securing social distancing, i.e. to count the number of people in a confined place. Nonetheless, the ability of radar ating frequency, and environments. Besides the different radar approaches and signal processing for reliable sensing, many new challenges for practical applications arise. In this paper, we review the state-of-the-art related applications and challenges of radar for combating the pandemic disease. Additionally, as a departure from the conventional approach, radar technique requires some basic explanation. This paper also provides an overview of radar sensing including its physical sensing basis.

Key words: Microwave Radar, Vital Sign Detection, COVID-19

1. INTRODUCTION

The emergence of potentially deadly COVID-19 (coronavirus disease 2019) caused by the Sars-CoV-2 (severe acute respiratory syndrome coronavirus 2) has become a global pandemic since late 2019. Victims of COVID-19 can develop a fever and sometimes shows respiratory difficulties such as shortness of breath with some severe cases lead to death. The virus was thought to encounter humans for the first time in a seafood market in Wuhan China and possibly carried by bats [1].

It has been reported that the virus is highly contagious. Respiratory droplets from infected people are dispensed through the process of sneezing and coughing can then infect other people via nose, eyes, and mouth when they are less than a 1-meter radius. Furthermore, the droplets can also be transmitted to others through surfaces contaminated with droplets. A study has shown that the COVID-19 virus can stay up several hours on surfaces [2]. Another main factor is that the infected person can be very contagious in the early stage of the infection and yet show no symptoms at all. This makes them unknowingly spreading the virus. Due to these factors, the virus is classified as very contagious and thus, easily spread from its origin in China throughout many countries in the world and eventually declared as a pandemic in January 2020 [3].

The COVID-19 pandemic has highlighted methods and tools in combating the disease. Many countries around the world have implemented lockdown and movement restrictions to reduce virus transmission among their citizens. Currently, social distancing is among the best strategy to reduce the spreading of the virus until a new treatment or vaccine is found. Citizens are advised to keep a safe distance of more than 1 meter from others in public spaces [4]. Nevertheless, such large-scale implementation is not easy to implement, for example, people still need to go to train stations and parks. In such a context, radar can potentially play a role in facilitating the rules of social distancing. Additionally, combating the pandemic also requires public health intervention at individual and community levels. Mass screening of potential COVID-19 infected persons can provide early detection and action that can be taken to isolate the suspected person from a healthy community. Screening provides an early indication of the presence of disease.

In literature, a lot of pandemic screening devices have been proposed with the main aim of detecting the disease based on the signature pattern and sign of infection. However, because the disease is highly contagious, any touch-based screening system would increase infection risk and not be welcomed by the person-to-be-tested. For this reason, non-contact screening tool such as the forehead infrared thermometer is preferable. Nonetheless, the screening process based on fever alone is still a loose criterion for suspected or confirm diagnostic of COVID-19 disease since other health conditions such as having common flu can also show the same symptoms. In a case study in Taiwan, it is reported that only 29.2% of COVID-19 cases were detected in airport arrivals screening [5].

Recent advancements of radar (radio detection and ranging) sensing technology over the last decades have extended the use of this technology from defense and security into civilian applications including non-invasive health sensing. Radar offers many advantages in health sensing including the use of low health risk non-ionising electromagnetic waves, the ability to penetrate thick clothing and walls, and low-cost. Furthermore, radar does not require very accurate placement in setup unlike other non-invasive sensors such as laser Doppler vibrator requires to tend to require very accurate placement which is not practical for field sensing.

Great advances have been in academia with radar been investigated for cardiopulmonary signs monitoring, fall detection for elderly people, human body imaging such as bone, cancer, heart, and tissues, and cough detection. Despite Numerous works of literature that have reported its advantages in health sensing, very few literature discusses the use of radar for combating the COVID-19 pandemic. The goal of a radar system is to be used in actual deployment as a reliable, accurate, and cost-effective complement or alternative to existing screening and detection technologies to contain the pandemic. Undoubtedly, there are opportunities for radar sensor in helping to stop the recent pandemic, On the other hand, there is also challenges for radar sensors before they can live up to the expectation of accurate and reliable sensing. Within this framework. this paper provides an overview of the state-of-art of radar sensing for health applications relating to the control of the COVID-19 pandemic for screening and social distancing. For this reason, we first present the fundamental concept of radar for health sensing, after that, we review of radar for accurate health sensing, and finally, we discussed the issues and challenges for implementing radar in for pandemic control.

2. COVID-19 SYMPTOMS FOR DEVELOPING STRATEGIES OF RADAR DETECTION

With the number of confirmed COVID-19 cases increased with time and accumulation of clinical data reported in the literature, we provide some indicators of COVID-19 symptoms related to the lungs and heart based on some public health reports.

COVID-19 has a mean incubation period of about 5 days. Symptoms usually start with unspecific symptoms such as fever, dry cough, and fatigue [6]. Several body systems may be involved, including respiratory symptoms - cough, shortness of breath, and chest pain). By rank, the most common symptoms are having a fever (83%-98%) followed by cough (76%-82%) and shortness of breath (31%-55%) [6]. However, about 39% of patients had the disease progresses to respiratory distress and acute respiratory distress syndrome (ARDS) in 8 and 9 days. Additionally, many patients infected with the new coronavirus also experienced heart problems. Reports also showed that about 44% of infected people developed arrhythmia [7] – a problem with the rate and rhythm of the heart. In this case, the heart would beat too slow or too fast.

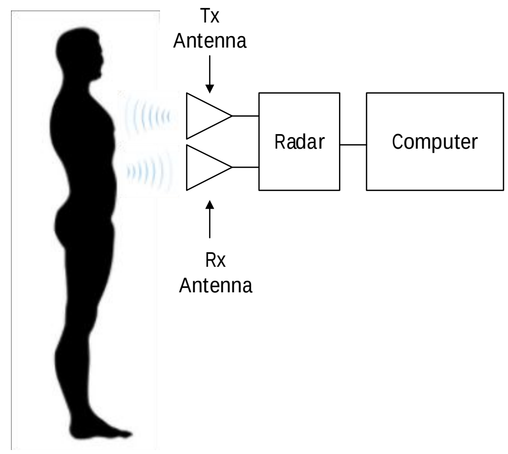

Figure 1: An example of a radar set up for vital signs screening

3. PRINCIPLE OF RADAR FOR PHYSIOLOGICAL SIGNS SENSING

In general, radar is a system that emits radiofrequency waves (RF) in a certain search volume in space. If an object is present the spatial volume, the object reflects a part of the transmitted energy to radar. The radar echoes are processed to extract information about the object such as velocity, distance, and location in space.

Contactless monitoring using Doppler radar for health application has been proposed in 1972 [8], and experimentally demonstrated two decades ago. The working principle of radar is based on the Doppler effect – a phenomenon where the transmitted wave by the radar changes its frequency and phase when it comes upon a target in motion. Fig. 1 illustrates a radar system for cardiopulmonary sensing using a continuous-wave (CW) radar. The radar is faced directly with the person's chest. The main radar system consists of radar with a transmitter and receiver antenna and a computer. The radar generates a continuous wave (CW) of a fixed frequency through the transmitter antenna and radiates the microwave energy to the chest of the person-under-test. By the Doppler effect, the transmitted wave undergoes a phase delay which is proportional to the distance between the chest and the radar [8]. Because the breathing and heart activity is cyclical, the observed phase shift is proportional to the chest surface displacement caused by breathing and heart activity.

Upon receiving at the radar receiver, the reflected signal is demodulated and filtered to a produced baseband signal or simply know as an intermediate frequency (IF) signal. This signal contains a constant phase shift which dependent on the distance of the chest from the radar and also cyclical phase shift due to the periodic chest motions. Since the since lungs and heart activity produce a small displacement of the body surface, the signal from these movements is weakly modulated into the radar echo. Furthermore, environmental noise, i.e. unwanted random body movements also exist during the vital sign acquisition process. Due to the unwanted noise, the IF signal is filtered and to an appropriate level for further processing. Subsequently, the IF signal is digitised using an analogue to digital converter (ADC) on the computer. Upon this stage, the signal waveform obtained is similar to the one found in the electrocardiogram (ECG) signal. Finally, the computer estimates the breathing rate and heart rate either directly from the IF signal (time-domain) or converting the IF signal into a frequency spectrum (frequency-domain) for analysis. Additionally, time-frequency analysis of the physiological signal can provide good insights to interpret the signal patterns.

A variety of radar can be used for health applications. Most studies used CW radar due to its low-cost hardware and simplicity in signal processing. Nonetheless, CW radar cannot measure range. A version of CW radar that can measure range is frequency-modulate continuous-wave (FMCW) [9]. The range information has benefits vital sign detection in 2 ways; improvement in detection accuracy by integrating range information [10] in the detection algorithm and the capability of cardiopulmonary detection of multiple persons [11]. Additionally, the use of multiple output multiple input (MIMO) antenna can provide information on the location of a person in space. Recently, ultrawide-band (UWB) radar has also been studied for vital sign sensing. The advantages of UWB radar compared to CW radar are better spatial resolution (chest displacement), lower level of electromagnetic radiation power, and physically small size for a complete device [12].

A wide range of frequencies has been tested for cardiopulmonary monitoring. This covers from frequency of 1 GHz to 100 GHz) [13]–[16]. However, among the many carrier frequencies, the ISM band frequencies with center frequency - 2.4 GHz, 5.8 GHz, and 24 GHz are the most investigated ones because of the vast availability of radar modules and microwave components at relatively low-cost. Literature shows that radar operating at higher frequencies such as K-band (i.e. 24 GHz) radar has shown to be more sensitive for detecting very small chest movement (less than 1 millimeter) than the radar with the lower carrier frequency, i.e. 2.4 GHz [17], [18]. This advantage is vital for detecting very small chest displacement caused by heart activity. Nonetheless, lower frequency radar offers simple signal processing in detecting chest movement [19]. Processing methods such as small-angle approximation can be inexpensively applied to decent microprocessors.

4. MAIN APPLICATION OF RADAR IN COVID-19

Existing radar systems such as the cardiopulmonary sensing system discussed in Section 2 can be used for screening tools.
The same approach can be used to detect the COVID-19 infection on a person because the disease affects the normal cardiopulmonary process. In the same manner, other radar applications – cough detection and social distancing control have potential use in the COVID-19 pandemic. To provide readers with basic information on these radar applications, the following sub-sections discuss the capability of state-of-the-art radar detection.

4.1 Cardiac Monitoring

Cardiac monitoring is one of the most promising radar applications in healthcare. The use of radar is mainly focused on extracting two important health variables; 1) heartbeat rate and 2) heart rate variability (HRV). The heartbeat rate is a measure of the heart beat-to-beat period while HRV is a measure of beat-to-beat variations. In both measurements, the heartbeat measurement is based on the detection of two consecutive signal peaks recovered from the radar reflected signal.

The ability of radar in detecting cardiac signal has been evaluated extensively. Successful detection has been reported for short-range conditions (< 1 meter) with most of the detection performed at a range between 30 to 80 centimeters. Nevertheless, reliable detection was also found at a longer range of 3 meters [20], though some research indicates a significant decrease of heartbeat measurement accuracy with a range of more than 20 centimeters [21]. Additionally, placing the radar at different chest position affect the detection accuracy. The study in [22] showed that placing the radar in front of the chest yields the best accuracy of more than 80%. Nonetheless, placing radar at a person's femoral, arm, and back of the chest also produces detection with detection percentage between 73% to 92% [23]. In this arrangement, the radar does not measure chest displacement, but rather the displacement of the blood vessel which proportional to the heart activity. Additionally, cardiac signal detection has been acquired in standing, sitting and lying positions with detection accuracy are higher in lying position (supine position) than standing or sitting position [19].

4.2 Respiratory Monitoring

Changes in respiratory signals one of the most important indicators for assessing health. An abnormal respiratory signal can be an important sign of physiological decline. At present, these irregularities are measured by monitoring the two variables 1) breathing rates and 2) respiratory tidal volume [24].

The reliability of radar for respiratory monitoring has been examined in various settings. The orientation of the radar towards the person-in-test has a major impact on breathing estimation accuracy. The error on breathing estimates may increase up to ten times depending on the angle [25]. In general, radar produces the strongest breathing signal when the radar directly facing the upper body part of the person-in-test [26]. In this arrangement, the detection accuracy can achieve more than 90%. Nevertheless, [27] found this arrangement can produce a higher error because the radar not only receives the signal from the chest but also small motion from the abdomen. While most work performs breathing detection when the person is stationary and breathing normally, radar has also been shown capable of monitoring breathing in walking positions [28]. For example, radar can identify a person who is having a normal, erratic, or stop breathing during the walking process.

The detection of anomalies in breathing patterns is important for successful intervention strategies for the pandemic because some breathing patterns are related to health conditions. Unlike the detection of breathing rates, the detection of breathing patterns requires the use of artificial intelligence such as a neural network (NN) and support vector machine (SVM). Several works have shown that the radar system can classify breathing patterns with a high degree of accuracy. Some examples of successful breathing pattern classifications and their reported accuracy are found in [29] [30]. with detection capabilities for normal breathing (100%), Cheyne-Stokes breathing (100%), Dysrhythmic breathing (80%), Kussmaul's breathing (93%), Cheyne variant Stokes breathing (90%), dysrhythmic breathing (87%), Biot's breathing (100%) and Kussmaul breathing (92%).

4.3 Cough Detection

Coughing is another sign of deterioration caused by irritating substances in the airways. Monitoring the frequency of coughing can give an idea of the progress for some diseases. Radar has been reported to detect cough alongside the heart rate and breathing signal. In [31], they showed that radar has 100% sensitivity to cough motion. This is because coughing produces an abrupt signal with a higher power in most frequencies compared to the normal breathing and heart activity. Thus, it is easier for radar to detect the coughing pattern [31]–[33].

4.4 Social Distancing

The objective of social distancing to create safe space between persons that are not households. To practice social distancing, one must distance themselves sufficiently. In most countries, the recommended safe distance is at least 1 or 2 meters between two non-household people [3]. Nonetheless, social distancing may not be easy to be practice. For example, managing large crowds in public spaces requires an understanding of crowd traffic flow and density management. The ability of radar to measure the distance, speed and location of a target in space can be used as a tool to enhance social distancing. To date, there is very little literature on radar application for social distancing.

There are several applications of radar that can maintain social distancing. Radar can be used to enhance social distancing in confined places to prevent overcrowding problems. Such control can be achieved in three ways – (1) counting people going in and out of confined spaces, i.e. rooms, (2) count the number of people in a confined space, and (3) measure the density of people per square meter.

Counting the number of people going into and out of a building or a room.
In practical implementation, a radar sensor can be mounted on the top side of a door to view people going in and out of a door. The detection of movement flow (going in and out) of the door can be estimated using low-cost CW radar with quadrature signal processing [34].

Counting the number of people in a confined space.
Radar can be used to count the number of people in a confined place. Such an example can be found in [35], where they used UWB radar to count the number of people in a lift. Experimental results showed that the radar was able to count the number of people in a lift in a random position with high accuracy (87%). Furthermore, UWB has also been used to count people in different confined environments such as room, building lobby, and people queuing in open spaces. experimental results show that the system produced accurate counting all of three conditions [35].

Estimating the density of people per square meter.
Thirdly, radar can be used to estimate the density of people per square meter. In [36], radar was used to investigate the density of people per square meter walking randomly in a constrained area. Results show that radar can estimate density with high accuracy (> 80%).

5. CHALLENGES

The discussion in previous sections shows how radar can contribute substantially in remote monitoring of human cardiopulmonary function and to measure the number of people in confined spaces. Surprisingly, the use of radar for contactless diagnostic and to secure social distancing for the

COVID-19 pandemics is still hardly exploited in practice. Many of the radar studies were successful in monitoring vital signs and counting persons but the use of radar is practically non-existent during this recent pandemic. It seems like radar is undervalued technology and requires a significant amount of further research and positive general positive perception for reliability in practical conditions. Thus, the following paragraphs discuss several challenges that need to be addressed

5.1 Random body motions and Environment Clutter Reduction

One of the most practical problems that can inhibit radar for cardiopulmonary sensing is the spurious body movement. Despite many good results found by researches, the measurement of heart and breathing signal were performed when the human subject is stationary and measurements were performed in a very stationary environment conditions, i.e. no people walking around and no moving equipment such as ceiling fans. When the person is stationary, the radar reflected signal is mainly modulated with the heart and chest signal. In practical measurement settings, unwanted movements such as random body movements – moving legs, chest, and movements from environments- are difficult to control. In this condition, the radar received signals from a wide range of frequencies, including, frequencies that are the same or close to cardiopulmonary signals [37].

The elimination of random body movements and environment clutter in the radar received signal for optimal detection of physiological signs remains an open challenge. Several approaches have been proposed to reduce the effect of random body movements. These include arctangent demodulation [37], adaptive phase compensation [38], and radar array system/ multiple transceiver system [39]. Other signal processing methods for reliability improvements to mitigate random movements can be found in [40]–[44]. Additionally, robust signal processing is also needed to remove the unwanted artifacts in the received signal.

5.1 Harmonics and Near-DC Respiratory Signal Issue

The phase demodulation of breathing signals from a human target contains the breathing frequency together with its much higher amplitude harmonics. Additionally, there is a bit different in the chest displacement due to breathing and heart activity. The problem arises when trying to measure breathing rate and heart rate monitoring simultaneously because the large amplitude harmonics of breathing signal interfere with the accurate detection of the heartbeat signal. Breathing harmonic cannot be filtered. A robust signal processing is required to solve this issue. One example of the efforts is the use of a harmonic cancellation algorithm [45].

Furthermore, the chest displacement caused by breathing (inhaling and exhaling air) and heart activity during normal breathing activity varies from 4 mm to 12 mm and 0.2 mm to 0.5 mm respectively [28]. In frequency rate, the respiration rate at rest varies between 0.1 Hz and 0.3 Hz, while the heartbeat rate changes in the 1 Hz to 3 Hz. Such very low frequency is very close to the DC signal (0 Hz) and thus, bound to have some distortion in many stages of radar processing, i.e. AC coupled radar architecture.

5.2 Extensive Field experiment

The capability of the radar discussed in the previous sections is mostly studied in laboratory conditions and controlled conditions. Using radar in the actual environment is a challenging issue. There is a need to study issues related to actual measurements. Radar may be susceptible to environment clutter and EM interference. Furthermore, the current study is limited to small samples of human subjects. There is a need for reliability assessment for a more diverse mix of people and types – age, gender, and height. Therefore, the study of radar that is robust to the above parameters is required for actual implementation. Additionally, some benchmark of the radar system and processing method on a set of tasks can provide benchmark and valuable information for standardisation.

5.2 Standardisation

Another open issue for the pandemic application is the standardization of the technology. Currently, various operating frequency between 1GHz to 100 GHz has experimentally demonstrated. However, several issues must be considered for real-world applications. As discussed, the previous section, a choice of suitable frequency is a tradeoff between the complexity of signal processing and sensitivity. Moreover, the radar system must not be a source of electromagnetic interference to other wireless systems such as automotive radar. The implementation of radar must follow the specific rules of frequency use and rules and regulations of medical devices.

5.1 Commercial Challenge

Apart from the technical challenges mentioned in the previous sub-sections, one of the non-technical issues that radar would have to face for practical use is competition from other well-established sensing technologies such as chest band and fitness tracker watches for cardiopulmonary monitoring, and video camera for social distancing monitoring. As discussed before, although radar-based sensing has advantages such as low-cost, unaffected by environment lightning, and has no privacy issue, it lacks in public confidence as radar technology was previously limited to the military and some very specific applications which is less known to the public and authorities. Nonetheless, recently, there are several start-up companies based on radar technology. For example, Xandar Kardian [46] for continuous vital sign monitoring at home.

6. CONCLUSION

Contactless health sensing technology has been considered as an important measure to prevent the spread of infectious disease. Radar as a non-contact sensor opens new opportunities in the area of pandemic control. Radar is shown to be low-cost, low health risk, and no privacy issue. In this paper, we discussed the capability and challenges of radar technology in cardiopulmonary signs and social distancing monitoring. Firstly, we provided an overview of radar technology and, how radar remotely estimates human vital signs. We then presented the radar effectiveness in monitoring vital signs and detecting abnormal conditions of vital signs. Furthermore, we presented how radar can secure social distancing. For each application of the radar, we examined the level of reliability found in the recent literature. Finally, we discussed technical and non-technical open issues and provide some probable solution and potential research in the future to solve and mitigate the issues.

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