COVID-SENSE: Radar-based Remote Respiratory Disorder Detection in Clinical Environment

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***Abstract*—The COVID-19 pandemic urgently requires contactless medical monitoring to prevent human-to-human interactions. Respiratory rate and respiratory irregularity are important indicators to classify the stages of COVID-19. Thus, respiration measurement is essential for the doctors to decide on medical treatment during hospitalization. In this work, the radar-based internet of things (IoT) system was implemented in inpatient ward, and the respiratory disorder assessment algorithm was proposed to help to identify the different COVID-19 stages. Data of COVID-19 patients in different symptoms' stages were collected continuously for one week. The experimental results show the proposed system can accurately detect the real-time respiratory irregularity in a remote and convenient way. The results of detection are also consistent with the diagnosis of clinicians, which indicates the proposed system can provide a safe and reliable way for the daily health monitoring of hospitalized COVID-19 patients.**

***Index Terms*—COVID-19, respiratory disorder, IoT, remote detection, Doppler radar sensor,**

I. Introduction

COVID-19 has become a global epidemic, seriously affected more than 700 million people worldwide, including more than 6 million deaths according to world health organization (WHO) records. The pandemic of the Omicron variant in China at the end of 2022 has resulted in a significant increase in hospitalizations.

Respiratory monitoring is an essential aspect of COVID-19 management. COVID-19 primarily affects the respiratory system and can lead to severe respiratory distress, which can be life-threatening [1]. Regular monitoring of respiratory parameters such as respiratory rate, oxygen saturation, and lung function can help detect early signs of respiratory distress, allowing for timely intervention and potentially preventing severe complications. Moreover, COVID-19 is known to have a highly variable disease course, with some patients exhibiting mild symptoms while others develop severe respiratory failure [1]. Respiratory monitoring can help healthcare providers track disease progression and adjust treatment plans accordingly. Besides, accurate respiratory monitoring can also be used to assess the effectiveness of treatments.

However, the daily respiratory monitoring in hospitals often relies on contact devices such as electrocardiograms, oximeters, etc. In order to prevent human-to-human interactions, hospitals urgently need a non-contact sensor to monitor patients' activities and COVID-19 related symptoms, like respiration disorder.

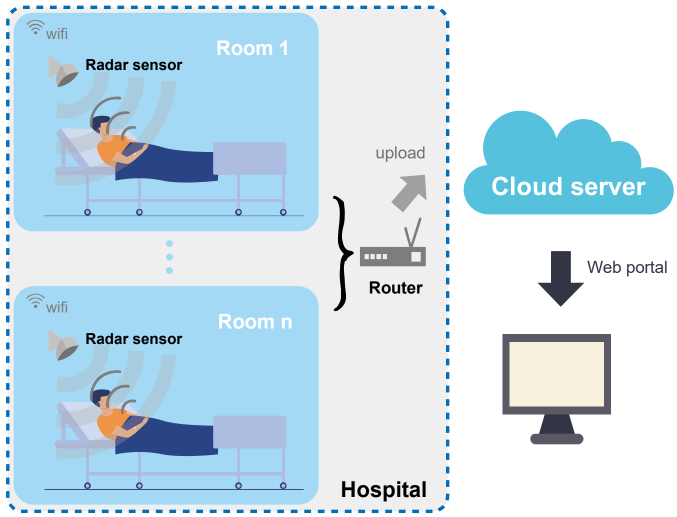

Fig. 1. The potential implementation of the proposed system into hospital care management.

Conventional non-contact vital sign monitoring methods mainly include camera-based solutions and millimetre-wave radar-based solutions. Camera-based solutions are limited by lighting conditions and privacy risks, which make it difficult to guarantee the accuracy and consistency of vital sign detection. In many studies in the past, it has been proved that the radar can accurately obtain the displacement of the chest cavity caused by the breathing movement of the human body [3]. Radar-based monitoring method does not violate privacy. Moreover, it can continuously monitor the real-time respiratory movement, not just the breathing rate, which make it effective in real-time respiratory distress detection, like apnea [3].

One of the typical symptoms of the COVID-19 is respiratory irregularity. The obvious feature is the instability of breathing amplitude and breathing rate. The non-contact monitoring system is highly desirable in hospital.

In this work, a radar-based internet of things (IoT) network was implemented in inpatient wards, and a respiratory disorder assessment algorithm was proposed to help identify the different COVID-19 stages. Data of the COVID-19 patient in different symptoms' stages was collected for one week, which means the process of the patient from severe illness to recovery was recorded. The experimental results show the proposed system can sensitively detect the real-time respiratory irregularity in a remote and convenient way. The results of detection are also

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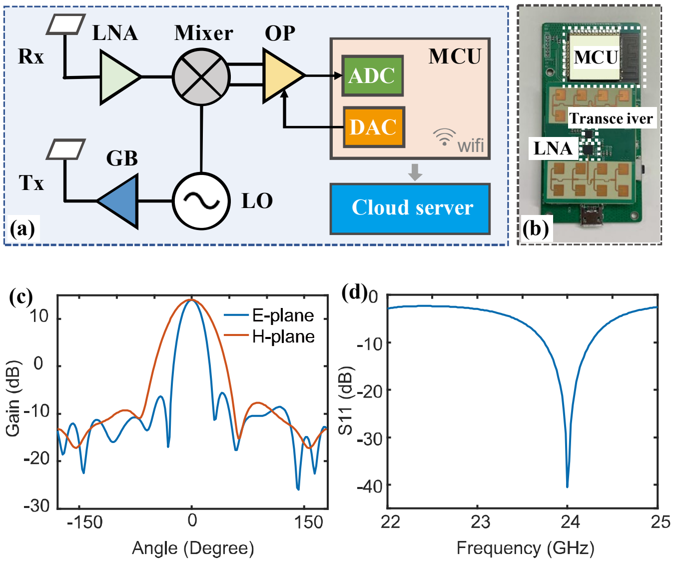

Fig. 2. Design and implementation of the 24-GHz DRS. (a) Block diagram. (b) Board-integrated DRS with a Bluetooth interface. (c) The radiation patterns of the series-fed patch array. (d) The S_{11} characteristic curve of the antenna.

consistent with the diagnosis of clinicians, which indicates the proposed system can provide a safe and reliable way for the daily health monitoring of hospitalized COVID-19 patients.

II. Method

A. Doppler Radar Detection for Respiratory waveform

The respiratory waveform can reflect information such as the frequency and depth of breathing. It plays an important role in timely detection of respiratory abnormalities, assessment of disease severity, and provision of data support.

The basic principle of remote respiratory waveform detection is relying on the linear phase demodulation to recover the phase change of the radar echo. For a typical Doppler radar, after the downconverter process, the detected in-phase (I) and quadrature-phase (Q) signals scattered by the skin can be obtained:

$$B_I(t) = A_I \cdot cos[\frac{4\pi x(t)}{\lambda} + \frac{4\pi d_0}{\lambda} + \varphi_0] \qquad (1)$$

$$B_Q(t) = A_Q \cdot sin[\frac{4\pi x(t)}{\lambda} + \frac{4\pi d_0}{\lambda} + \varphi_0] \qquad (2)$$

where A_I and A_Q are the amplitudes of the signals, respectively, φ_0 is the residual phase noise, $x(t)$ is the displacement of the chest surface due to cardiopulmonary activity, λ is the wavelength of the radar carrier, and d_0 is the initial distance between the radar and the measured human.

To extract the chest motion $x(t)$, the arc-tangent/arc-sine demodulation technique can be used to obtain the phase information from the I/Q-channel signals [3].

Due to the recovered displacement signal is a combined motion consisting of the respiratory motion and heart motion. To obtain the respiratory waveform, we used a smoothing filter to remove the heartbeat waveform and leave the respiration waveform.

Fig. 3. The experimental setup in in-patient ward. The insert is the picture of the radar sensor.

B. System Description

In the healthcare industry, IoT (Internet of Things) systems are becoming increasingly popular due to their ability to improve patient care. In hospital, IoMT (Internet of Medical Things) with its set of benefits such as enabling real-time monitoring, providing a more mature and effective solution to collect patient data, and tracking the activities of patients.

In this work, we built a preliminary radar-based IoT system in several wards in the hospital's inpatient area to collect patient daily data, as shown in Fig.1. The system includes a radar sensor that is placed in the room or on the patient's bed, which collects data on the patient's vital signs and sends it to a central platform or dashboard. The central platform or dashboard can be accessed by healthcare providers, who can use the real-time data to monitor the patient's health status and detect any changes or potential health problems early.

Raw radar data is sent to Alibaba Cloud's RDB database 1 through the MQTT queue of the MCU in real time. The algorithm script in the cloud server obtains the newly written record from database 1, and immediately writes it into the specified entry of RDB database 2 after calculating the index. At the same time, it is also sent to the terminal background for visual UI display. The whole system can help healthcare providers take prompt action to prevent complications and improve patient outcomes.

III. Experiments and Discussion

A. Measurement setup

A custom-designed interferometric radar operating at 24GHz is employed in the experimental part. Fig. 2(a) shows

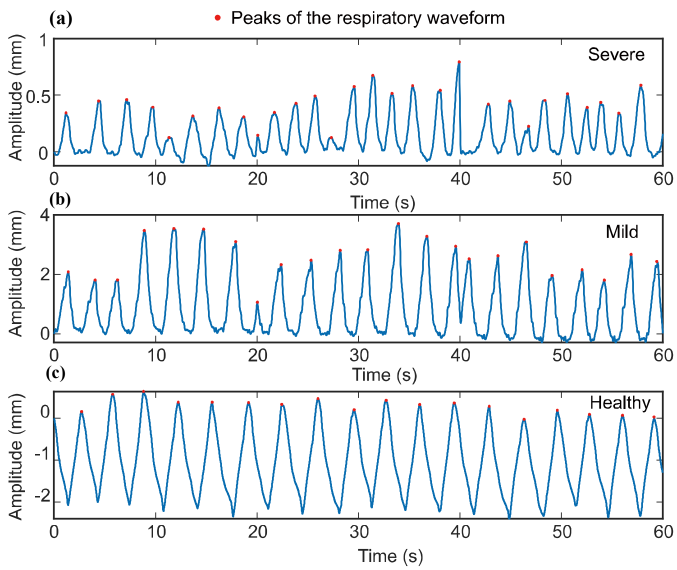

Fig. 4. The respiratory waveforms of different COVID-19 stages obtained by proposed system in hospital. (a) Severe stage. (b) Mild stage. (c) Recovery.

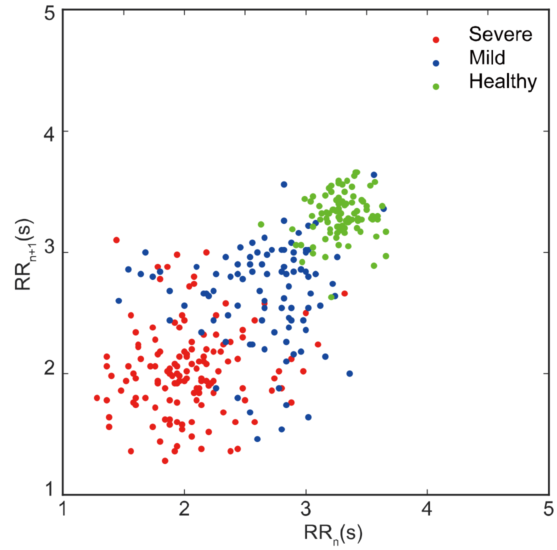

Fig. 5. The respiration-to-respiration (RR) intervals plot of different COVID-19 stages.

the block diagram of the radar sensor used for remote respiration detection based on a 24-GHz millimeter-wave integrated circuit (MMIC). Fig. 2(b) shows the implemented board-integrated radar sensor. The substrate used is Rogers 4350B, whose dielectric constant and the loss tangent are 3.48 and 0.0037, respectively. The 2*4 linearly polarized antenna array was printed on the same PCB layer with the MMIC, achieving minimized size and avoiding potential losses and impedance mismatch due to the use of millimeter-wave cables and adaptors. The gain reaches 14.02 dBi, with 3-dB beam widths around 24.7° and 45.8° in the E- and H-planes, respectively, as shown in Fig. 2(c). The S_{11} of such antennas is given in Fig. 2(d).

B. Data collection and analysis

Fig. 3 shows the system setup in the inpatient ward. The radar sensor is fixed on the wall at the head of the bed, 60cm away from the bed surface, and 40 degrees from the surface of the radar to the wall.

The subject was hospitalized in severe condition and recovered a week later. The process of the patient from severe illness to recovery was recorded by the implemented system. The written informed consents were obtained from the patients.

Fig. 4 shows the 1-minute respiratory waveforms of three patients obtained by proposed system in hospital. The red points marked the peaks of respiratory waveform. It can be seen that COVID-19 patient with severe illness showed severe respiratory amplitude irregularities compared with the respiratory waveforms of mild illness and healthy condition, which is consistent with the clinical experience of doctors.

Moreover, the breathing cycle of severely ill patients is also significantly shorter than that of mildly ill and healthy condition. In order to evaluate the stability of this breathing cycle, we extracted the respiration-to-respiration (RR) interval through the peak finding algorithm. Following the principle of the Lorenz Plot of heartbeats [4], RR scatter diagram was generated on the X–Y plane by plotting all the respiratory intervals in the observation segment window with the preceding interval as the x value and the subsequent interval as the y value. Fig.5 shows the RR plot of 5-minutes time window. It can be seen that as the disease worsens, the respiratory scatter points will become closer to the zero point in the RR plot, and the scatter points will become more scattered. This suggests that more severe conditions lead to more severe breathing irregularities and shorter breathing cycles.

IV. Conclusion

In this work, a radar-based intelligence of things (IoT) network was implemented in inpatient wards, and a respiratory disorder assessment technique was proposed to help identify the different COVID-19 stages. The data of COVID-19 patients in different symptoms' stages were collected for one week. The obtained patients' respiratory waveforms and the proposed respiration-to-respiration (RR) intervals plot shows the proposed system can sensitively detect the respiratory disorder, which indicates the proposed system can provide a safe and reliable way for the daily health monitoring of hospitalized COVID-19 patients.

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