CHAPTER 17

Internet of Things use case applications for COVID-19

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17.1 Introduction

The Internet of Things (IoT) is an arising technology enabling communications between various types of sensors or devices that would enhance the quality of our daily life in different domains (Jara et al., 2009). Recent statistics predict that the number of IoT devices will grow exponentially in the coming years and reach 125 billion IoT devices by 2030 (Statista, 2019). These devices transmit data by using network technologies, which enables easy communication between machines and humans. IoT technology could achieve substantial improvements by integrating various technologies such as Machine Learning (ML) (Adi et al., 2020; Aledhari et al., 2020), blockchain (Ekramifard et al., 2020; Połap et al., 2020; Reyna et al., 2018; Yazdinejad et al., 2021), etc., which opens great areas for applying IoT technology in different domains such as education (Gul et al., 2017), industrial settings (Da et al., 2014), healthcare (Islam et al., 2015), smart homes (Kamaludeen et al.), security (Saharkhizan et al., 2020), etc.

Healthcare is one of the domains that has received significant benefits from using IoT technology by reducing costs, improving health services, and enhancing the user's experience (Islam et al., 2015; Qi et al., 2017). Recent studies have also confirmed the role of IoT technology in this domain where the market value of IoT technology is expected to reach more than USD 188 billion in 2025 (Marketsandmarkets, 2020).

In December 2019, a severe contagious disease caused by coronavirus 2, called COVID-19, was appeared in Wuhan, China for the first time (Sohrabi et al., 2020). COVID-19 is a deadly airborne disease transmitted in respiratory droplets. Due to the high infection and death rates of COVID-19, the World Health Organization (WHO) declared this virus a

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pandemic after only 3 months (Cucinotta & Vanelli, 2020). This novel severe respiratory syndrome coronavirus 2 has killed a large number of people (more than 2.6 million), which makes it one of the deadliest pandemics in history (WHO, 2021). COVID-19 symptoms could be close to the flu's, such as, fever, muscle pain, and sore throat. In addition to flu symptoms, COVID-19 could also demonstrate loss of taste or smell, symptoms that are crucial to diagnose the virus early (CDC, 2021a). The incubation period of a patient infected with COVID-19 could last up to 14 days, which increases the chance of virus transmission (Lauer et al., 2020). Surprisingly, some people could be infected without showing any specific symptoms. As a result, quarantining infected patients and asymptomatic patients would be essential to stop the chain of transmission (Güner et al., 2020). Moreover, for the COVID-19 dilemma, dealing with confirmed/suspected cases is critically important, which has caused health authorities to apply different guidelines such as wearing masks and washing hands more frequently. Although these guidelines have efficiently reduced the negative impacts of coronavirus, applying different technologies, including Artificial Intelligence (AI) (Vaishya et al., 2020), ML (Shahid et al., 2021), IoT (Nasajpour et al., 2020), etc., could greatly assist with mitigating this virus. In particular, IoT has empowered authorities with different remote capabilities such as monitoring and diagnosing to lessen the number of infections and deaths.

In this chapter, we focus on the state-of-art IoT applications for the current pandemic and how those devices can support both patients and healthcare professionals in combating COVID-19 in different phases. In our study, we investigate the role of IoT devices and applications in five main categories: monitoring, diagnosing, tracing, disinfecting, and vaccinating. We focus on how IoT technology could improve the performance of healthcare services and mitigate the impacts of COVID-19 on patients, healthcare providers, government authorities, and communities. Table 17.1 demonstrates the perspective of the proposed approaches in these task areas.

The remainder of this chapter is organized as follows: we first demonstrate the key role of IoT within the current and future pandemics in Section 17.2. Then, Section 17.3 covers the IoT applications to diagnose and detect patients infected with COVID-19. Section 17.4 demonstrates the monitoring aspect of COVID-19. Other tasks of tracing, disinfecting, and vaccinating will be discussed in Sections 17.5, 17.6, and 17.7 respectively.

Table 17.1 IoT applications during pandemics.

Application	Concentration	Ref.	Purpose	Sensor(s) / Method(s)	Communication	Task
Indoor monitoring	Safety rules	Petrović and Kocić (2020)	Cost-effective guidelines monitoring	Temperature and thermal camera	MQTT	I
		Fazio et al. (2020)	Cost-effective navigation system	Mobile sensors	BLE	I
		Bashir et al. (2020)	Cost-effective SOP monitoring	Temperature and ToF	WebSocket	I
	Air quality	Mumtaz et al. (2021)	Regularly air quality capturing	Gas and particle/NN and LSTM	ATmega328P and NodeMCU WiFi Chip	I
	Surface contamination	Stolojescu-Crisan et al. (2020)	Contamination reducing	Temperature and motion	WiFi	I
	Occupancy monitoring	Fernández-Caramés et al. (2020)	Securely occupancy level monitoring	Bluetooth and NFC	MQTT and Node-RED	I
Symptoms monitoring	Blood saturation	Miron-Alexe (2020)	Vital signs remote monitoring	Oximetry	WiFi	I
	Respiratory signs	Valero et al. (2020)	Cost-effective respiratory signs monitoring	Pressure	WiFi	I
		Al-Shalabi (2020)	Respiratory signs monitoring	Temperature	WiFi	I
		Chloros and Ringas (2020)	Mapping potential contamination areas	Temperature	Bluetooth	I
Airport maintenance	Controlling factors	Sales Mendes et al. (2020)	Airports spread preventing	PIR and ToF and temperature and humidity	LoRa	I
Health condition systems	Cloud-based IoT	Akhbarifar et al. (2020)	High risk patients monitoring	Bio-sensors/K-Star and RF and SVM and MLP	MQTT	I
	Robotic system	Kanade et al. (2021)	Assisting hospitals with better patient's management	Temperature	Bluetooth	I
	COVID-SAFE	Vedaei et al. (2020)	Distance and vital signs monitoring	Temperature/decision tree and SVM and PPG	WiFi and cellular and LoRa	I

(*Continued*)

Table 17.1 (Continued)

Application	Concentration	Ref.	Purpose	Sensor(s) / Method(s)	Communication	Task
Symptomatic patient	Finger-touch	Hasan (2021)	Fever detecting for stopping the spread	Ultrasonic and RFID and temperature	MQTT	II
	Bracelet	Cacovean et al. (2020)	Infected patients detecting	Temperature and heart rate and GPS	WiFi	II
	Smart helmet	Mohammed, Syamsudin, Al-Zubaidi et al. (2020)	High-temperature detecting of passers-by	Thermal camera	WiFi and GPS	II
	Smart glasses	Mohammed, Hazairin, Syamsudin et al. (2020)	High-temperature detecting of passers-by	Temperature	WiFi	II
	Drone	Mohammed, Hazairin, Al-Zubaidi et al. (2020)	High-temperature detecting of passers-by	Temperature	WiFi	II
	Robotic	Karmore et al. (2020)	Cost-effective system diagnosing patients	Temperature and ABS and GSR and ECS and EMS	WiFi	II
Asymptomatic patient	Smart hospital	Abdulkareem et al. (2021)	Hospital's workload reducing and infected patients detecting	NB and SVM and RF	Cloud	II
	Medical imaging	Ahmed et al. (2020)	Reducing workload and detecting infected patients	Faster-RCNN and ResNet-101	-	II
	Health condition systems	Arun et al. (2020)	Detecting suspected cases	Oximetry and blood pressure	GSM	II
		Thangamani et al. (2020)	Detecting and preventing infections	Temperature and sound and blood pressure	GSM and WiFi	II

Social distancing violators	Wearable device	Kumbhar et al. (2020)	Identifying social distancing violators	CNN	Cellular	II
Smartphone-based	Automated tracing	Rajasekar (2021)	Tracing suspected cases	RFID	NFC	III
	IoTrace	Tedeschi et al. (2020)	Cost-effective secure tracing system	Totem	BLE	III
Wearable-based	Digital PPE	Woodward et al. (2020)	Performing proper social distancing	Received signal strength indicator	BLE and WiFi	III
	IoT-Q-Band	Singh, Chandna et al. (2020)	Preventing quarantine absconding	ESP32 kit	WiFi and GPS	III
	EasyBand	Tripathy et al. (2020)	Performing proper social distancing	Temperature and biosensor	BLE	III
Robotic technology	Sanitizer spraying	Mohammed, Arif et al. (2020)	Disinfecting areas without human interactions	Ultrasonic	GSM and GPS	IV
	Hand sanitizer dispenser	Eddy et al. (2020)	Providing disinfectant for people nearby Infrared Distance	Ultrasonic	GSM and GPS	IV
Drone	Sanitizer spraying	Mohammed, Syamsudin, Hazairin et al. (2020)	Disinfecting areas without human interactions	Optical camera	GPS	IV

ABS, Airflow Breathing Sensor; *BLE*, Bluetooth Low Energy; *ECS*, Electrocardiography Sensor; *EMS*, Electromyogram Sensor; *GSM*, Global System for Mobile communications; *GPS*, Global Positioning System; *GSR*, Galvanic Skin Response sensor; *MLP*, MultiLayer Perception; *MQTT*, Message Queuing Telemetry Transport; *NFC*, Near-Field Communication; *PPG*, Photoplethysmogram sensor; *ToF*, Time of Flight.

17.2 IoT key role in COVID-19

The adverse effects of coronavirus on different parts of society have created an essential need for different techniques to mitigate this virus. This could be achieved by first stopping the spread and then vaccinating people (Zhang et al., 2020). However, manually monitoring and diagnosing infected patients could result in latency, high costs, or even more infections.

IoT, as an emerging technology in healthcare, has delivered superior results by reducing costs and errors, improving user experiences and treatment procedures (Bhatt & Bhatt, 2017; Zhang et al., 2020). It has also been recognized as a reliable technology that can be utilized in different stages of COVID-19.

In this study as illustrated in Fig. 17.1, we investigate the role of IoT technology in combating COVID-19 in five separate stages: monitoring, diagnosing, tracing, disinfecting, and vaccination.

The world is dealing with a deadly pandemic, which has caused more than 2.7 million deaths as of March 20, 2021 (WHO, 2021). This opens an essential area for avoiding further contamination, where IoT provides various available remote monitoring applications. Basically, these applications are aimed to monitor people based on different measurements such as respiratory signs, social distancing practices, mask-wearing, and so on. In Section 17.3, we demonstrate the various IoT applications performing the monitoring task.

One of the first major tasks for mitigating COVID-19 is to diagnose people infected with this virus. This is being done by performing a combination of testing measures such as nucleic acid testing, protein testing, and Computed Tomography (CT) (Udugama et al., 2020). The earlier the virus is diagnosed, the faster and the better the treatment is. Moreover, isolating the patient would be more effective and as a result, the contamination rates would decrease dramatically. IoT technology could assist both healthcare professionals and patients in diagnosing COVID-19 and enhance the efficiency of the COVID-19 diagnosis procedure. In Section 17.4, the applicable IoT systems for diagnosing or detecting the coronavirus will be discussed.

In general, tracking infected or suspected patients plays an important role in combating COVID-19. This strategy is more highlighted during quarantine time and even after lockdown. Using different digital contact tracing techniques has shown promising results in the current pandemic

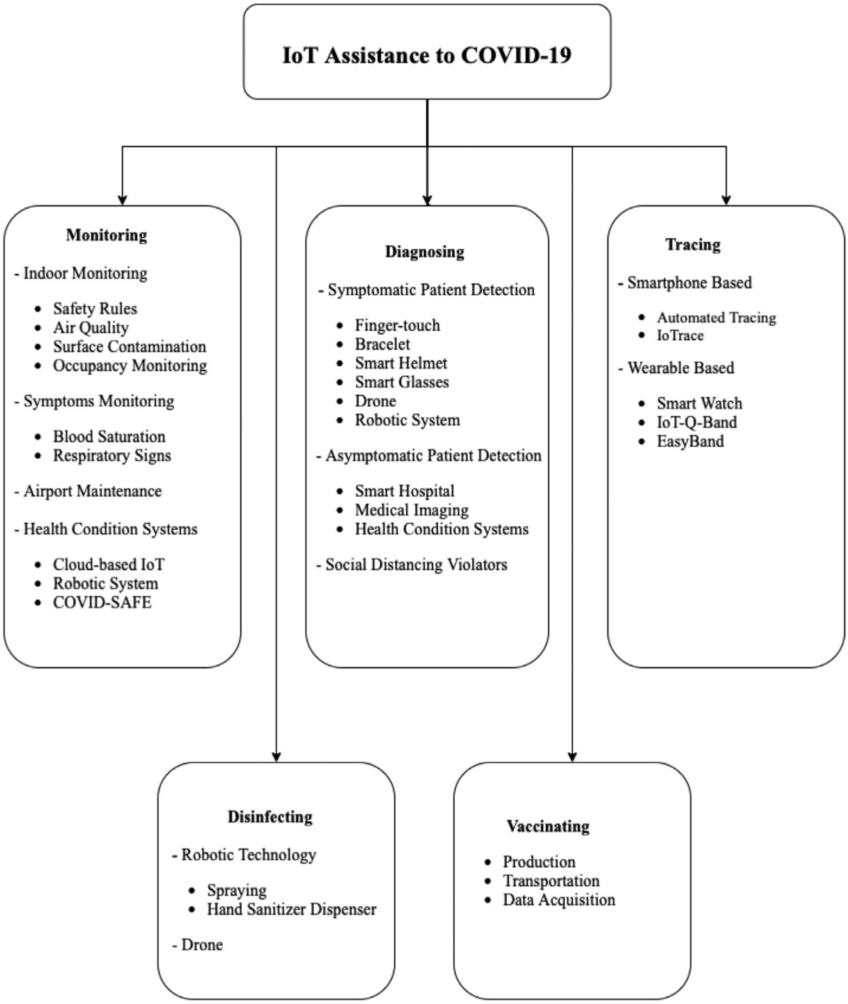

Figure 17.1 IoT applications to fight against COVID-19.

during which these technologies assist health authorities by detecting people who were in proximity of contaminated cases (Ferretti et al., 2020). Various interfaces such as Bluetooth Low Energy (BLE), Global Navigation Satellite System, etc. could be adopted for broadcasting captured data within the systems. In Section 17.5, we focus on the contact tracing applications that are embedded within the IoT devices to assist healthcare authorities with tracing tasks for different phases.

Another important task of IoT technology during the COVID-19 pandemic is the cleaning and disinfecting public spaces, surfaces, devices, etc. to prevent further transmission of the virus, which could happen either directly or indirectly (WHO, 2020a). As a result, different IoT-based devices such as robots and drones have been designed to accomplish those tasks. Section 17.6 will focus on the applicable utilization of IoT in this area.

The last key phase of the COVID-19 pandemic is vaccinating, which was first allowed for emergency use on December 11, 2020 (Oliver et al., 2020). Regarding the rapid production of COVID-19 vaccines and their effectiveness, the world might get back to normal life at the end of 2021 (Powell, 2020). However, the opposite might be true because of two factors. First, the vaccination timeline for the second dose might not be met by patients, and also the temperature of vaccines might not be monitored properly as it is crucial for some vaccines such as the Pfizer COVID-19 vaccine (Kim et al., 2021). Consequently, applying IoT technology to prevent such challenges could benefit and speed up the vaccination phase.

17.3 Monitoring

In the past several years, IoT technology has been widely deployed in different domains, particularly healthcare. A variety of IoT-based monitoring systems have been utilized for executing different tasks such as abnormal blood pressure detection, oxygen saturation, and glucose level. However, monitoring applications are not limited to vital signs, and the recent COVID-19 pandemic has increased the need for screening applications with respect to safety guidelines. The initial monitoring components during COVID-19 can be divided into indoors, symptoms, air maintenance, and health system monitoring applications as follows in the sections below. Taken together, these applications could reduce the workload, errors, and costs of manually monitoring (Haleem et al., 2020), which could potentially slow the spread of COVID-19.

17.3.1 Indoor monitoring

One of the major topics to be investigated during COVID-19 is the methods for stopping the chain of transmission among people. This virus could be transmitted from public surfaces located outdoors or even indoors. Although this remains an open problem in dealing with COVID-19, governments required measures such as social distancing, wearing masks, etc. to limit the spread of coronavirus. Moreover, the quality of consumable air by people has gained attention as well. We further focus on other applicable approaches to indoor monitoring by considering safety rules, air quality, surface contamination, and occupancy of a building.

17.3.1.1 Safety rules

Due to the required safety measurements from governments, various technologies have been developed to follow them accordingly for indoor areas. That being so, a safety monitoring system based on IoT technology was designed by Petrović and Kocić (2020). This system enables monitoring of three important aspects: temperature, mask-wearing, and physical distance. Additionally, the proposed system demonstrated an average accuracy of 87.5% and 69% for correctly detected mask-wearing and physical distance. This cost-effective system applies sensors and computer vision technology to monitor if the rules are being followed. In this case, the safety rules violators inside a building could be captured and alerted (Petrović & Kocić, 2020).

Another study was conducted on monitoring the proximity between people to ensure the practice of social distancing by people inside a building (Fazio et al., 2020). The authors of this research study adopted a low-cost IoT-based indoor navigation system for the prevention of gatherings. BLE was utilized for communicating among the users' smartphones using their beacons. As a result, an appropriate path will be provided based on the recorded beacons, so that the user could safely navigate inside the building. While the proposed configuration achieved a descent coverage and decreased interference, this approach can cover a broader zone using lower BLE Beacons. This not only reduces the costs but also enhances the energy efficiency.

Although the recent lockdowns effectively reduced the spread of COVID-19, they also caused the economic recession and unemployment soar (Bartik et al., 2020). However, reopening businesses was allowed for these reasons, it might increase the contamination level among society (Gregory et al., 2020). Therefore social distancing scenarios have been proposed to prevent the contamination and control the pandemic (Baqaee et al., 2020). In another attempt by Bashir et al. (2020), an IoT-based system equipped with a variety of sensors was proposed to ensure that standard operating procedures (SOP) against COVID-19 are being practiced. This low-cost system performed several tasks, including counting people, measuring temperature, and calculating the proximity. As a result, a real-time monitoring system with a centralized server was adopted for businesses and offices. Additionally, collected data from people did not include personal data, which preserved the privacy of users. Overall, this system is applicable to various sectors of SOP using different functionalities of contact tracing or distance violators detecting (Bashir et al., 2020).

17.3.1.2 Air quality

As most people of the world are following social distancing and stay-at-home orders, businesses have demonstrated a potential opportunity for remote working from home. Although this avoids expanding the contamination, it has impacted indoor air quality due to the widely applied lockdowns. This has caused a high increase in the pollutant levels of indoor areas compared to outdoor air quality (Kumari & Toshniwal, 2020). Since the coronavirus could be transferred through air, it is crucial to ensure buildings, including houses, offices, medical centers, etc., maintain a decent Air Quality Index. According to the (CDC, 2020a), the main pollutants could be carbon monoxide, nitrogen oxide, particle matter, etc. These pollutants can possibly enhance the risks of infection. Consequently, the concentration of these pollutants could deteriorate the death ratio of COVID-19 infections. Additionally, air quality monitoring is essential for vulnerable people with respiratory conditions (EPA, 2020).

With respect to the possible risks of air pollutants, indoor air quality monitoring has been carefully considered so that the risks for air consumers inside buildings could be lessened. During the COVID-19 pandemic, indoor contamination poses a crucial challenge for monitoring and enhancing air quality. Along with an IoT monitoring system for this purpose, Mumtaz et al. (2021) also proposed an ML analytic system to predict the rate of pollutants in the near future. In this study, continuous reports of the air quality conditions will be sent to a server, which could be monitored on a web interface and mobile application. This is where ML algorithms are applied to classify the captured air quality conditions, which Neural Network (NN) outperformed the rest of the algorithms. Besides, Long Term Short Memory (LSTM) was applied for the prediction of two other purposes including the air pollutants concentration and air quality. Altogether, the proposed sensing system achieved the highest accuracy of 99.1% and 99.37% for NN and LSTM, respectively. However, the sensors' life period and their calibration could be major challenges for the long-term use of this system (Mumtaz et al., 2021).

17.3.1.3 Surface contamination

After governments decided to reopen businesses, different requested rules were not enough to stop the spread of this virus. Disinfecting surfaces to prevent infections that could be caused by touching contaminated surfaces has gained considerable attention. However, it could be tough to minimize the contamination of surfaces only by disinfecting. To address that, Stolojescu-Crisan et al. (2020) proposed an approach for preventing the people from touching surfaces. This IoT-based system called qToggle adopts various technologies (sensors, Raspberry Pi, and smartphones) to better manage the surface contamination inside offices. qToggle enables various technologies, including objects and devices connected together on a robust Application Programming Interface. This system could perform tasks related to the objects inside a building, for example, opening and closing a door, turning on/off the lights, etc. Since users perform these tasks using a smartphone, surface contamination could be avoided to lessen the impacts of pandemic. In addition, qToggle could monitor the power usage of different appliances, which mainly helps with lowering the energy consumption during the quarantine (Stolojescu-Crisan et al., 2020).

17.3.1.4 Occupancy monitoring

With respect to the various preventive procedures (social distancing, wearing face masks, etc.) after reopening businesses, monitoring the occupancy of people within specific places could be crucial. This could matter more for overcrowded places such as public transportation. However, counting technologies (e.g., automated passenger counters) might not be efficient within overcrowded places due to counting errors. Consequently, an efficient alternative could be the adoption of various wireless identification technologies such as Radio Frequency Identification (RFID), Quick Response, etc. Fernández-Caramés et al. (2020) proposed an IoT system embedded with blockchain, which aims to monitor occupancy during the pandemic. The autonomous wireless devices were adopted to enable the system to be independent of active actions from users. The collected data do not maintain any personal information from users, which could enhance user privacy. Also, the use of blockchain within a decentralized manner could avoid security attacks. To evaluate the proposed system, estimating the occupancy level was considered within two facilities. The results demonstrated a sufficient accuracy for the estimated occupancy while having a low delay time. Overall, such an occupancy level monitoring system could ensure maintaining social distancing measures.

17.3.2 Symptoms monitoring

As mentioned, COVID-19 could be transmitted more quickly among people if the social distancing measures are not practiced. Since there are various symptoms that could appear in infected patients, there is also a need for monitoring these symptoms. However, it is critical to ensure normal people remain with good hygiene. This leads to a path of monitoring people who have been in close contact with confirmed cases because of the higher chance of infections they have. In the following sections, we will focus on proposed applications for monitoring blood saturation and respiratory signs of suspected/confirmed COVID-19 patients.

17.3.2.1 Blood saturation

Blood oxygen saturation has been considered as one of the major factors for evaluating the health condition of the lungs (Nocturnal Oxygen Therapy Trial Group, 1980). To assess the oxygen level of the blood, various tests have been adopted. However, pulse oximetry has been widely adopted as an indirect method for evaluating the health condition of breathing (Ortega et al., 2011). With respect to the current pandemic, monitoring infected patients, who are asked to be quarantined until recovery, is critical. For this reason, Miron-Alexe (2020) proposed an IoT application utilizing a pulse oximetry sensor to check on the heart rate and oxygen level of the infected quarantined patient. This system keeps health staff from being infected by preventing them from having physical contact with patients. The system provides virtual monitoring for physicians to ensure the patients' health. In comparison to a commercial pulse oximeter, the proposed approach demonstrated good accuracy while it could have lower energy consumption.

17.3.2.2 Respiratory signs

In addition to the aforementioned types of symptoms that infected patients could show, respiratory signs can be considered when diagnosing COVID-19. This could be potentially due to the damage that has been done to the patients' lungs. An effective method of evaluating the lungs' health is to perform pulmonary function tests inside hospitals. However, as a result of massive numbers of infected patients with severe symptoms, it is important to keep the suspected cases or patients with mild symptoms mostly isolated inside their homes. Consequently, monitoring these signs is essential for isolated patients during COVID-19. The R-Mon tool was proposed to monitor respiratory signs of isolated patients (Valero et al., 2020). Pressure sensors within this tool enable recording of the respiration rates of patients. This low-cost tool provides the collected data (including patients' conditions) using a cloud platform to be monitored and analyzed by physicians. In general, the authors demonstrated an mhealth tool that can be applied for real-time monitoring of patients that are suffering from pulmonary deterioration during COVID-19.

Similarly, a study based on IoT and Wireless Sensor Network was adopted by Al-Shalabi (2020) to monitor quarantined suspected cases, especially elderly people. This approach enables health providers to effectively monitor the captured health data, including the changes in the body temperature. Consequently, if the system detects any symptoms, it will alert the health provider regarding the patient's health situation. In this case, further actions could be applied to save the patient's life. The authors deployed a visualization technology called ThingSpeak to better clarify the data for physicians. The live monitoring of such patients enables physicians to assist more cases on a larger scale (Al-Shalabi, 2020).

As COVID-19 side effects are mainly similar to flu's, Chloros and Ringas (2020) proposed an IoT application, called Fluspot, for symptom monitoring. The main objective of Fluspot is to avoid the widespread of flu and also COVID-19. This application was developed by adopting three major technologies, including a wearable device, mobile application, and cloud. In addition, Fluspot provides a map of potential infections using collected temperature data from users. This makes users aware of possible contamination areas so that they can move on in a precautionary manner. Unlike most of the recently adopted applications, the proposed system could be applied worldwide even where there are internet limitations.

17.3.3 Airport maintenance

One of the major places that could easily worsen the spread of the virus are domestic and international airports where in some cases more than 300,000 travelers are transferred in one single day from a gateway. One of the big concerns in the airports with respect to COVID-19 contamination is the restrooms where it can easily be a part of transmitting the virus. As a result, maintenance and disinfection of those places are highly required within the airports. The crowd of people could increase the chance of contamination for each traveler, which means restrooms must be cleaned regularly. Sales Mendes et al. (2020) proposed an approach for toilets maintenance, which basically focuses on the status of various factors. Controlling factors such as soap level, distances, and temperature have been adopted in this system. Several sensors and technologies communicating with the LoRa protocol are enabled with a multiagent system. Additionally, the proposed approach demonstrated a successful monitoring system for those aforementioned factors inside an airport by minimizing the workload of the airport services and enhancing the cleanliness of the airport resulting in the users' satisfaction. Altogether, the proposed could prevent the spread of the virus among travelers inside the airport with minimized cost and energy consumption (Sales Mendes et al., 2020).

17.3.4 Health condition monitoring systems

With regard to the severity of COVID-19 treatment, it is important to keep patients with specific diseases safe from this virus. In general, COVID-19 could have severe impacts on patients dealing with serious diseases such as cancer, diabetes, and hypertension (Zaki et al., 2020). The need for computer-aided technologies has enabled researchers to apply various technologies such as IoT and AI to help those patients with underlying conditions. The major advancements of IoT and sensors within a cloud have been successfully implemented for different aspects of the healthcare domain. Consequently, different health systems have been developed for COVID-19. We will focus on the monitoring systems in the sections below.

17.3.4.1 Cloud-based IoT

To achieve a prediction system building on IoT and the cloud, data mining techniques, and ML algorithms have been applied for superior monitoring or diagnosing of patients with various health conditions (Kumar et al., 2018). Accordingly, Akhbarifar et al. (2020) proposed a monitoring system based on IoT and the cloud while the data collected by the cloud will be adopted to build an ML model. The model is focused on diagnosing patients with heart disorders and hypertension disease for whom COVID-19 could possibly be life-threatening. The analytical results are basically achieved using various algorithms including J48, Support Vector Machine (SVM), Random Forest (RF), etc., which will be sent to health staff for further actions. The authors also applied a lightweight encryption method within the system to maintain security. Ultimately, the outcomes of the evaluation demonstrated K-star as the best classifier with an accuracy of 95%, which demonstrates an effective and secure health monitoring system using the IoT and cloud (Akhbarifar et al., 2020).

17.3.4.2 Robotic system

Kanade et al. (2021) have proposed a robot-based approach, which can maintain detecting and remote monitoring of patients with a high risk of infection. The solution applied several technologies, including computer vision, Natural Language Processing (NLP), thermal camera, and autonomous navigation, to provide monitoring benefits to healthcare workers. The authors proposed two different scenarios during COVID-19 for managing patients in hospitals. The developed robot is empowered to perform different tasks within these two scenarios. Overall, this remote system could perform monitoring a patient's condition and providing virtual meetings with loved ones.

17.3.4.3 COVID-SAFE

AI-assisted technologies have been adopted within IoT systems, which could enhance the efficiency of real-time monitoring of pandemics. According to Vedaei et al. (2020), an IoT framework using AI was developed for monitoring the distance and vital signs of users. This framework (called COVID-SAFE) is built on three main elements, including a wearable device, smartphone application, and ML algorithms. The wearable device, empowered with various sensors, measures different health parameters, including body temperature, heart rate, etc., and also social distance. The smartphone demonstrates the results from those collected data regarding the health condition and contamination risk of users. Additionally, the data analyzed by the ML model considers the real-time spread of this contagious virus. In comparison with two other algorithms, including decision tree and SVM, the proposed method achieved a slightly better accuracy of 74.7%. Communications among these elements are placed by cellular data or LoRa enabling local communication within restricted areas (Vedaei et al., 2020).

17.3.5 Challenges

In the near future, IoT technology could widely assist the healthcare domain with its monitoring capabilities. This could be applied for various purposes as we discussed above. However, several challenges should be considered when developing a monitoring system based on IoT. Security and privacy of the collected data are critically important to assess for all sectors, especially healthcare. Regarding the safety guidelines applications, several important concepts could potentially lower the efficiency of the approaches. Briefly, the cost of deployment and installation in large scales, sensors maintenance, high communication bandwidth, and high energy consumption should be considered to achieve superior and reliable IoT systems. Taken together, the healthcare domain could be efficiently assisted using such devices delivering accurate results in the fight against COVID-19.

17.4 Diagnosing

A key point for combating all diseases is to first diagnose or detect them, which opens the area for physicians to manage treatment procedures of patients. As this increases the number of patients who are receiving care, there will be fewer infections in the society (Sabeti, 2020). Regarding the COVID-19, various types of measurements, including respiratory signs, lung nodules, have been identified for diagnosing infected cases. However, some of these symptoms, such as fever, cough, difficulty breathing, loss of taste, appear at the first stage of the disease (CDC, 2020b), These types of symptoms could be adopted to identify symptomatic patients. On the other hand, the asymptomatic COVID-19 patients could be detected using measurements such as changes in the oxygen saturation and respiratory rates. In the following sections, we further discuss recent research on the diagnosing task of IoT based on two types of symptomatic and asymptomatic patients. Then, we briefly demonstrate the importance of social distancing violators' detection.

17.4.1 Symptomatic patient detection

It is important to diagnose suspected cases of COVID-19 to stop the spread. One of the main symptoms of COVID-19 infection is fever. Therefore the rise in the infection and mortality rate of COVID-19 caused authorities to use thermometer guns to identify people with high temperatures, especially in public places such as airports and malls (WHO, 2020b). However, this could potentially increase the infection risk of health officers due to one-by-one screening in close contact. Additionally, if the number of people increases unexpectedly, health officers might not be able to screen all people in a crowd (Mohammed, Syamsudin, Al-Zubaidi et al., 2020). A better solution for detecting people with fever could be the adoption of smart thermometers. The advantage of these smart devices over manual temperature detecting devices is to expose staff to less risk of contamination. Industrial examples of such wearable devices on the market are Kinsa or Tempdrop. While these devices are worn by users, the temperature is recorded regularly to identify any new changes. In the following sections, we will focus on recent diagnostic IoT systems for symptomatic COVID-19 patients based on different applicable technologies.

17.4.1.1 Finger-touch

An alternative method for fever detection was proposed by Hasan (2021), which is basically an IoT system for remote detection of fever. The proposed system uses various types of tools within a cloud to efficiently avoid spreading the virus. Additionally, a microcontroller connected with a finger-touch temperature sensor captures any signs of fever. Also, this system is equipped with a motion detection tool to monitor the passersby close to the user. The monitoring manager is alerted via SMS regarding any new fever detection. Using the ThingSpeak platform, the captured data were presented for better clarifications for the users Hasan (2021). Overall, the application of Finger-touch devices could enhance the efficiency of symptomatic patients' detection.

17.4.1.2 Bracelet

An IoT system for detecting patients infected with the coronavirus was implemented by Cacovean et al. (2020). Various technologies have been adopted within this system to collaborate with health authorities to better fight the COVID-19 pandemic. The first is a wearable bracelet device equipped with three types of sensors to capture temperature, heart rate, and location. Using the assigned cloud database within this IoT system, collected information from patients is sent to physicians and health authorities. Moreover, different ML models are applied to analyze the cloud built-in model based on the patients' information. The highest accuracy was achieved by the Logistic Regression model, where 81% of the samples were accurately classified whether they are suspected of COVID-19. As the model demonstrated efficient results in COVID-19 diagnosis, it could be used for combating COVID-19 within national health systems.

17.4.1.3 Smart helmet

A smart helmet, a wearable device, enables detecting the high temperature of passers-by within the crowd. Mohammed, Syamsudin, Al-Zubaidi et al. (2020) developed a smart helmet for monitoring the temperature of people by using thermal and optical cameras. This IoT-based system aims to lessen human involvement for better control of this pandemic. Additionally, real-time data collected from suspected cases, including the person's face image, body temperature, and Global Positioning System (GPS), will be shown on an assigned smartphone so that authorities can take proper actions regarding the infected case. The deployed software in this system along with various proposed methods had reduced the human error while capturing temperature quickly and efficiently (Mohammed, Syamsudin, Al-Zubaidi et al., 2020).

17.4.1.4 Smart glasses

Another application could be the use of smart glasses, which reduces close contacts and interactions among healthcare professionals and people. An IoT-based system equipped with face detection technology was developed by Mohammed, Hazairin, Syamsudin et al. (2020) to detect suspected cases that demonstrate signs of fever. Then, the captured data by health officers using these glasses (temperature and face image) will be sent to health authorities for further action. In addition to the reliability of the collected data, smart glasses could significantly reduce the spread of COVID-19 due to the lower interactions. One industrial example is Rokid, which enables monitoring and detecting people with fever in a crowd.

17.4.1.5 Drone

Slowing the spread of coronavirus by detecting the users with high temperature could be practical. In addition to the two previous wearable devices, an Unmanned Aerial Vehicle (UAV) could be developed for early diagnosis of COVID-19. Mohammed, Hazairin, Al-Zubaidi et al. (2020) proposed an IoT-based system empowered with sensors, thermal and optical cameras, etc. Authorities could be empowered by this system having the benefit of accessing hard-to-access areas. Also, they will be notified by the alerts from the UAV device. Since this system is not dependent on a health officer for temperature screening in the crowd, it potentially prevents COVID-19 from spreading. Moreover, virtual reality could be a satisfactory additional tool for visualizing collected data. In

Canada, the Pandemic Drone has shown decent results for not only fever detection in a crowd but also monitoring various respiratory measures (Cozzens, 2020).

17.4.1.6 Robotic system

In a study, authors aimed to focus on an IoT-based robotic system to assist the health community for better diagnosis of COVID-19 (Karmore et al., 2020). They claimed this humanoid system is a cost-effective approach for medical practitioners while it could stop the spread of the virus by performing a complete test considering the COVID-19 infection of the user. The main principles of this approach could be divided into various technologies, including sensors, medical imaging, cameras, blood samples, and autonomous navigation. Utilizing real data from adopted technologies for feeding the ML models, this system could be used as a diagnostic tool for assisting healthcare authorities to fight against this pandemic. Although ResNet50 achieved a decent accuracy for diagnosing COVID-19, it is predicted that developing a decentralized NN algorithm would enhance the accuracy while reducing security issues.

17.4.2 Asymptomatic patient detection

COVID-19 can be diagnosed using the aforementioned patient symptoms. However, infected patients are not always symptomatic. This disease could also infect people without showing any symptoms, e.g., fever, cough, etc. Considering the possibilities of asymptomatic infections, COVID-19 could be more dangerous for patients due to the latency of diagnosis. Also, an asymptomatic patient could easily spread the virus among people whom he/she has been in close contact with (Nishiura et al., 2020). In the following sections, we focus on different IoT-based approaches for diagnosing asymptomatic patients infected with COVID-19.

17.4.2.1 Smart hospital

The next generation of hospitals could be smart hospitals, which are impacted by the emergence of IoT technology. This kind of hospital enables various functions including diagnosing, treating, managing, and decision-making that are linked together (Yu et al., 2012). Additionally, implementing an actual smart hospital for a community requires the hospital to conform to different concepts of informative, intelligent, and digital hospital (Jinjun, 2010; Yu et al., 2012).

With respect to the advancements within ML and IoT, a study demonstrated the effectiveness of these two technologies within a smart hospital environment during this pandemic (Abdulkareem et al., 2021). The authors proposed an ML model using three different algorithms of RF, Naive Bayes, and SVM to diagnose patients infected with COVID-19. The impact of IoT within this model is to collect the data from RT-PCR, CT-scan, and X-Ray images, then it transfers them to the appropriate storage. This allows ML models to diagnose COVID-19 patients. After applying the algorithms on a normalized dataset along with a feature selection technique, SVM performed more efficiently with higher accuracy of 95% achieving better diagnosis results. In addition, this model can help medical staff to avoid overcrowding within a hospital and reduce the workload (Abdulkareem et al., 2021).

17.4.2.2 Medical imaging

One of the main methods of diagnosing and screening COVID-19 patients is using medical images including X-ray and CT scan (Kassani et al., 2020). This enables great resources of imaging data for further analysis with ML technologies. Ahmed et al. (2020) proposed an IoT-based DL framework for diagnosing patients infected with COVID-19. The framework has different capabilities such as reducing the workload pressure, managing the pandemic, and, more importantly, diagnosing infections. The DL architecture is built upon two developed benchmarks: Faster-RCNN and ResNet-101 (He et al., 2016; Ren et al., 2016). The authors adopted the required data from various medical imaging datasets, which were stored accordingly, enabling the IoT-based DL framework to detect COVID-19 contaminated cases. As the study claims, the developed model outperformed the recently adopted DL frameworks with an accuracy of 98% for early diagnosis of COVID-19 (Ahmed et al., 2020).

17.4.2.3 Health condition systems

Several systems based on IoT have been developed to focus on detecting infected patients. These health condition approaches are basically considering the respiratory signs using various sensors. In a study, authors (Arun et al., 2020) proposed an IoT system, so that these suspected cases could be detected and quarantined faster. Various technologies, including Raspberry Pi, sensors, GPS, etc., have been adopted for asymptomatic patient detection and health condition monitoring. Based on the results captured by the pulse oximeter, the system determines the need for isolation if a patient is suspected to COVID-19. If a patient is isolated, the COVID-19 infection will be considered based on the collected data, including blood pressure, and heart rate, from adopted sensors without having any close contact. In addition, the proposed approach enables physicians to monitor those patients during their quarantine period. The essential need for such approaches could also prevent potentially serious damage to the lungs (Arun et al., 2020).

With respect to the COVID-19 chain of transmission, it is important to detect and prevent infections. To do so, Thangamani et al. (2020) developed an IoT system for predicting the symptomatic or asymptomatic infections to this virus. The adopted system is built on various sensors for capturing different vital characteristics of patients, including body temperature, cough detection prototype, and blood pressure. From all these metrics, the chance of infection from COVID-19 can be indicated. For example, if the patient's cough rate is higher than normal, an alert will be sent to health providers for further follow-ups. The authors used Arduino to connect and manage the adopted sensors. Moreover, they provided a last examination using pulse oximeter sensors to discover asymptomatic patients. This could possibly detect if sufficient oxygen is being transmitted to different parts of the body. By predicting infected cases, the spread of this virus could be better handled (Thangamani et al., 2020).

17.4.3 Social distancing violators

In addition to COVID-19 negative effects on societies, it also has caused a recession in almost every country's economy. Therefore businesses have to reopen as soon as possible to avoid further downturns. This caused authorities to assign social distancing guidelines to reduce infections. However, the chain of transmission could not be stopped due to some people that violate these guidelines.

Kumbhar et al. (2020) developed a paradigm that is based on IoT wearable technology. They applied several technologies, including surveillance cameras, wearable devices, and cellular devices. Taken together, they could identify violators of social distancing requirements in a timely manner. Moreover, areas with a high risk of infection can be detected. The authors evaluated the efficiency of their model using object detection with Deep Learning (DL) and a simulation by Python for spread detection. The adopted model using the Convolutional NN method achieved 90% accuracy for distance violators detection. Consequently, users' activities could be monitored and traced for better reducing the chain of transmission.

17.4.4 Challenges

Applying IoT technology for early detecting and diagnosing COVID-19 patients could bring numerous exponential benefits to the healthcare system. However, various challenges have to be considered to enhance the efficacy of the applications. Since COVID-19 was started in late 2019, the number of datasets containing real-world data is limited. Also, the existing ones could be wrongly labeled. Such datasets could impact the results of the diagnosis. Additionally, choosing the right algorithms and methods for making proper predictions could be critical. Due to the massive use of IoT devices for symptom detection (such as pulse oximeter, thermometer), another challenge in this area could be considering the battery life of the devices.

17.5 Tracing

The widespread of the virus among people within public areas or business offices has led researchers to focus on implementing different IoT-based approaches using contact tracing technology. This provides major methods to the healthcare system for tracing the infected or suspected cases.

With respect to the exceptional benefits of adopting IoT along with contact tracing technology, a study introduced an IoT-based contact tracing system (IoT-CTS) for facing pandemics (Hu, 2020). The authors determined the various applicable sensors based on their type, including location and vision. The main perspectives for designing an architecture of IoT-CTS have been addressed within this study. In the following two sections, we discuss different proposed IoT and contact tracing applications based on smartphones and wearables.

17.5.1 Smartphone-based

During the recent COVID-19 outbreak, numerous smartphone applications have been developed for different phases of the pandemic (Nasajpour et al., 2020). These contact tracing applications such as Stop Corona (Stopcorona, 2020), TraceTogether (Tracetogether, 2020), Hamagen (Stub, 2020), etc. were mainly designed to slow and stop the spread of the coronavirus. Embedding IoT with smartphone devices could greatly benefit the tracing phase of COVID-19. We further discuss two recently proposed tracing systems based on IoT and smartphones.

17.5.1.1 Automated tracing

The vast number of confirmed and suspected cases could lead to needing an automated model with low cost of adoption where it can enable authorities to better stop the spread by avoiding new infections. However, contact tracing itself might not be able to achieve the aforementioned advantages. This persuaded the authors to propose an IoT-based approach using two different technologies (Rajasekar, 2021). They implemented the RFID Tag for labeling suspected cases, so they could be traced by the authorities. Moreover, a smartphone application was implemented, so that the user could be alerted whenever a case crosses a smartphone (within a specific radius). This system outperforms the manual tracing by demonstrating higher efficacy, requiring less workers, decreasing the chance of absconding. Also, it could enable real-time monitoring of the cases. Taken together, the pandemic could be managed to reduce the negative effects of COVID-19.

17.5.1.2 IoTrace

The authors proposed a privacy-preserving IoT-based architecture for performing contact tracing tasks using a smartphone (Tedeschi et al., 2020). IoTrace was basically developed to address different challenges associated with the IoT contact tracing systems such as users' privacy and communication's latency. Briefly, privacy and security, communication, and computation costs were considered in this distributed model, which enhanced the privacy of the user's collected data by adopting k-anonymity (Wang et al., 2019). They have adopted a threat model for demonstrating the effectiveness of their architecture against privacy attacks in two areas: location and health status. Moreover, it reduces the overhead communications between devices, which makes it more cost-effective than the regular contact tracing approaches.

17.5.2 Wearable-based

Wearable devices have been widely adopted within healthcare sectors for mainly self-monitoring patients (Appelboom et al., 2014). These devices could be extremely helpful for isolating patients during COVID-19. According to the CDC (CDC, 2021b), isolating people who show symptoms of COVID-19 such as fever, coughing, shortness of breath, etc. is essential. People who have been in close contact with confirmed cases should also be quarantined. On the other hand, after authorities decided to reopen businesses, people were asked to follow social distancing rules. Moreover, contact tracing of people could potentially reduce the spread of the virus by alerting the people who are violating the rules. These two main objectives have created a great opportunity for applying wearable devices. Here we discuss three recently developed IoT applications utilized within this sector.

17.5.2.1 Digital personal protective equipment—smart watch

Due to the need to reopen businesses, governments attempted to adopt different technologies to provide safer environments. One of the main practices during this pandemic is to maintain social distance to mitigate contamination. To ensure the correct practice of this method, Woodward et al. (2020) proposed a low-cost approach using wearable IoT technology and tracing sensors. They implemented personal protective equipment (PPE) using the BLE interface, which can be adopted within different sectors of daily life including public areas and work offices. The model, called Digital PPE, is equipped with a smart watch. Overall, the proposed system alerts users about any violation of social distancing with an accuracy of 90%. Digital PPE could possibly omit any privacy concerns, high costs for adoption, etc. compared to the contact tracing approaches using smartphone applications.

17.5.2.2 IoT-Q-Band

IoT-Q-Band was designed by Singh, Chandna et al. (2020) to track people who are not following isolation principles. This wearable band prevents isolated patients from leaving their assigned areas. The web interface connected to these devices enables authorities to continuously track the patients. Moreover, losing or taking off the band will also notify the authorities so that they can follow the conditions of patients by alerting or calling them. This device is connected to a smartphone application through Bluetooth. The authors validated their approach with the performance of four different samples based on whether the cloud system detects any radius changes from a specific distance. Consequently, the system performed accurately by tracing absconding cases. Similarly, real-time use of electronic wristbands/bracelets has been adopted in Hong Kong and the United States (Hui, 2020; Izaguirre, 2020).

17.5.2.3 EasyBand

Regarding the huge number of people coming back to work, it is important to ensure required physical distancing measures are being followed. EasyBand was developed for this purpose based on the Internet of Medical Things (Tripathy et al., 2020). The workflow of this wearable device is to demonstrate any possible risks of infection by tracking the user's close contacts with other people. The users are given no warnings as long as they maintain the appropriate distance. However, if users meet at a distance less than 4 m, the device will alert the users with a careful or critical warning based on the distance. This is performed by the BLE, LED, etc. equipped within the system. EasyBand is independent of using smartphones, and it could be adopted as a standalone device for tracking cases. Similarly, various industrial wearable tools such as Safe Spacer (Safespacer, 2021) and Proximity Trace (New Equipment, 2021) have been adopted among different workplaces to effectively alert violators of social distancing measures.

17.5.3 Challenges

During the COVID-19 pandemic, the healthcare domain demonstrated an essential need for tracing suspected and confirmed cases. This encouraged researchers to develop IoT applications to lower the contamination and spread of this deadly virus. However, such approaches could not be as cost-effective as the manual tracing systems. Moreover, most of the approaches require people to have a smartphone. Also, many approaches make users to carry or wear devices. As a result, this could be understood as a privacy concern to users, which requires the developers to consider privacy and security issues within their implementations. Finally, many devices might not be reused for another case due to the chance of contamination.

17.6 Disinfecting

COVID-19 has brought many challenges to healthcare and government authorities. It can be transmitted between all ages of people through droplets produced by sneezing or coughing from infected cases. These droplets containing the virus do not vary based on the symptomatic or asymptomatic nature of patients; they can be present in both types (Velavan & Meyer, 2020). Most importantly, they could easily survive on various object surfaces and in the air for various amounts of time. As an example, droplets could survive on stainless steel materials for 3 days (Van Doremalen et al., 2020). With respect to the importance of COVID-19 mitigation, disinfecting areas could prevent the spread of coronavirus. Manual disinfection could be practical, but it still exposes people to the risks of contamination. Various approaches based on IoT technology have been proposed, which we focus on in the next sections.

17.6.1 Robotic technology

As we discussed, breaking the chain of COVID-19 transmission is crucial for authorities. This opens an area for disinfecting methods using various technologies such as IoT, AI, and so on. One important technology that has been adding value to healthcare is robotics. It has been applied for various purposes including different surgical operations, radiosurgery, and so on (Bogue, 2011). Here, we focus on adopting the system for disinfecting areas contaminated by coronavirus.

17.6.1.1 Sanitizer spraying

Mohammed, Arif et al. (2020) designed a system for disinfecting areas utilizing IoT and robotic technology. They performed the disinfection by spraying sanitizer on surfaces. Additionally, the system is equipped with the ability of spraying long distances, which is moderated by an optical camera and an autonavigation vehicle. This robot was developed to reduce human involvement in disinfecting surfaces.

17.6.1.2 Hand sanitizer dispenser

As the authorities adopted several approaches to reduce human interactions, the need for cleaning hands regularly is crucial. However, as we mentioned, touching surfaces could pose a high risk of infection. Here, this is due to the use of sanitizer bottles. Similar to other approaches, human interactions should have been reduced to avoid further spread of this virus. Accordingly, robotic technology was designed based on the IoT system, so that hand sanitizers could be dispensed among people without touching surfaces (Eddy et al., 2020). Additionally, the proposed robot enables spraying the sanitizer whenever anyone waves his/her hands close to the robot's infrared sensor. In this case, the robot will detect the hands and perform the sanitization.

17.6.2 Drone

The chance of infections from touching surfaces has led to increased sanitizing and washing of hands. However, another possible way to get infected is by airborne transmission. According to the CDC, droplets produced by coughing or sneezing from infected people could survive hours suspended in the air (CDC, 2021c). Utilizing drones within large buildings for disinfecting could be a potential solution.

An IoT-based system was developed for disinfecting areas using UAVs technology (Mohammed, Syamsudin, Hazairin et al., 2020). The authors implemented their system aiming to lessen the workload for maintenance staff by remotely sanitizing the areas. To efficiently moderate these IoT-based drones, they were equipped with optical cameras. Also, communicating with the people close to the drone was enabled using a speaker, so that they could be notified about the disinfected areas. Finally, the locations of these areas will be sent to the system for better management. An industrial example of this type of drone is Spanish authorities have adopted Da-Jiang Innovations (DJI), a UAV-based company, for disinfecting contaminated areas.

17.6.3 Challenges

As the COVID-19 virus could last a significant amount of time on various surfaces, it is important to develop different IoT-based approaches to facilitate manually disinfecting and sanitizing surfaces. Although various tools and methods have been proposed using IoT for this purpose, it is important to consider the existing challenges. As we discussed previously, battery life could be one major issues of working with IoT devices. It could be highlighted when considering disinfection of large areas. Finally, the high price of deployment could limit applications only in essential areas such as hospitals.

17.7 Vaccinating

After a year of confronting COVID-19, the first vaccine was issued by the US Food and Drug Administration in December 2020 (FDA, 2020). As the world is trying to combat this virus, various types of vaccines (including Pfizer-BioNTech, Moderna, Johnson & Johnson, etc.) have been approved to prevent further infections of COVID-19 (CDC, 2021d). Although vaccinating people has reduced the contamination and death toll, there are some factors that need to be considered to get the best results from vaccines. Briefly, the challenges are production, transportation, and management of injections. Regarding the importance of vaccination, various technologies, especially IoT and Blockchain, could greatly assist the healthcare system in dealing with these challenges. It is important to note that since vaccination is in its first stage, the research conducted on this area is limited. We will demonstrate three potential parts of vaccination.

17.7.1 Production

Regarding the widespread of coronavirus, medical manufacturers are trying to produce vaccines to quicken the process of vaccinating people. However, social distancing measures have reduced the number of workers, which opens an area for automation. Moreover, a huge amount of time is required to produce a vaccine, which could be lessened by adopting IoT, AI, etc. As discussed, IoT devices have been adopted in various fields of healthcare with respect to COVID-19. The IoT sensors could possibly reduce the amount of work by measuring various parameters during the vaccine setup. Screening physical distances and air quality within the workplace would also be other advantages of IoT during vaccine production (Sisto, 2021).

17.7.2 Transportation

The next stage of vaccination is the distribution of vaccines to the health sectors. Here, the major challenge for the vaccine rollouts is to store them safely during transportation. Therefore it is critical to maintain the required temperature for the cold chain of vaccines (Hanson et al., 2017; Matthias et al., 2007). Temperature changes of the vaccines could lead to weakness or could even be dangerous for the patient (Hibbs et al., 2018). Since the quality of COVID-19 vaccines is extremely dependent on temperature, different technologies could be applied for vaccine transportation and distribution. Using IoT sensors, the cloud, blockchain, etc., authorities can efficiently monitor the temperature changes of the stored vaccines. This enables healthcare facilities to capture the locations of inappropriate storage temperature (Kaplan, 2020). For this purpose, different types of systems could be implemented to ensure the safe transport of vaccines. Cloudleaf and Varcode, examples of IoT technology, are respectively using Bluetooth and barcode to safely distribute the vaccines by monitoring different measures and alerting about essential actions (Smith, 2020; Whipple, 2021). Moreover, Fulzele et al. (2020) also designed an IoT-based cold box for maintaining the appropriate temperature. This box is also equipped with location monitoring as well.

17.7.3 Data acquisition

The last stage of dealing with public vaccination is to make sure people get their vaccines. Some vaccines, including Pfizer and Moderna, require two doses to be effective. Regarding the date for the second shot, users should be notified about getting it on time. Consequently, IoT wearable devices could be applied to remind them of their shot (Marsh, 2021). Additionally, the hospital's record-keeping could be improved by these devices for providing treatments for the future. Moreover, the adoption of vaccine passports for different places such as airports and business offices could possibly be a solution for getting back to normal life.

17.7.4 Challenges

As IoT devices could be proposed to reduce the rate of degradation due to the temperature drop during the production and transportation of the vaccines, there are still security challenges that need to be considered. One main challenge is to ensure the IoT sensors will work securely and properly. An example of security concerns could be adversary attacks, which attempt to perform malicious activities such as deleting or changing the collected data from sensors and making false transactions (Singh, Dwivedi et al., 2020). Battery life of the deployed sensors is critical to consider while applying inside the cold boxes for temperature monitoring. Finally, countries started to define vaccine passports for travelers who are vaccinated. As these passports will require private information, it is essential to consider privacy concerns (Albano, 2021).

17.8 Conclusion

As governments are planning to vaccinate people, COVID-19 will possibly become endemic. This means the virus will circulate seasonally similar to the flu (Denworth, 2020). As a result, it is likely that the world has to overcome COVID-19 each year, which could be achieved by adopting different technologies. As we noted, IoT technology could be extremely helpful during pandemics by assisting healthcare professionals, authorities, and patients in different stages such as monitoring, diagnosing, tracing, disinfecting, and vaccinating. In each task, we reviewed the IoT proposed technologies or systems based on different concepts applicable to each task. Although the current IoT applications have positively enhanced the efficiency of the fight against COVID-19, it is essential to improve these proposed systems regarding different possible challenges. Privacy and security of the data collected from patients are extremely important to be considered in future IoT systems.

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