Internet of Things for Current COVID-19 and Future Pandemics: An Exploratory Study

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Abstract—In recent years, the Internet of Things (IoT) has drawn convincing research ground as a new research topic in a wide variety of academic and industrial disciplines, especially in healthcare. The IoT revolution is reshaping modern healthcare systems incorporating technological, economic, and social prospects. It is evolving healthcare systems from conventional to more personalized healthcare systems where patients can be diagnosed, treated, and monitored more easily. The current global challenge of the COVID-19 pandemic caused by the novel severe contagious respiratory syndrome coronavirus 2 presents the greatest global public health crisis since the pandemic influenza outbreak of 1918. By the moment this paper was written, the number of diagnosed COVID-19 cases around the world reaches more than 14 million. Since then there has been a rapid rise in the different research communities to combating this worldwide threat and IoT technology is one of the pioneers in this area. In the context of COVID-19, IoT enabled /linked devices/applications are utilized to lower the possible spread of COVID-19 to others by early diagnosis, monitoring patients, and practicing defined protocols after patients recovery. This paper surveys the role of IoT-based technologies in facing with COVID-19 and reviews the state-of-the-art architectures, platforms, applications, and industrial IoT-based solutions combating COVID-19 in three main phases including early diagnosis, quarantine time, and after recovery.

Index Terms—Internet of Things, Medical IoT, COVID-19, IoT, Industrial IoT, Healthcare, Pandemic, Coronavirus, Infectious Disease.

I. INTRODUCTION

The term Internet of Things (IoT) was first coined in a presentation about implementing Radio-frequency identification (RFID) in the Protector and Gamble company by Kevin Ashton for supply chain management [1]. IoT is an advanced technology that can link all smart objects together within a network with no human interactions [2]. More simply, any object that can be connected to the internet for further monitoring or transferring data has the opportunity of being an IoT device [3]. In recent years, IoT has drawn convincing research ground as a new research topic in a wide variety of academic and industrial disciplines, especially in healthcare. The IoT revolution is reshaping modern healthcare systems incorporating technological, economic, and social prospects. It is evolving healthcare systems from conventional to more personalized healthcare systems where patients can be diagnosed, treated, and monitored more easily. IoT is increasingly becoming a vital technology in healthcare systems where it can deliver lower expenses, a better quality of services, and advanced user experiences [4]–[7]. As a result of its wide capabilities including tracking, identification and authentication, and data collection, the exponential growth of IoT in healthcare from USD 72 billion in 2020 is expected to reach USD 188 billion in 2025 [8], [9].

The current global challenge of the COVID-19 pandemic caused by the novel severe respiratory syndrome coronavirus 2 presents the greatest global public health crisis since the pandemic influenza outbreak of 1918. According to the last report of the World Health Organization (WHO), as of July 19, 2020, the number of confirmed COVID-19 cases passed 14 million people with an approximate huge deadly rate of 540 thousand people [10]. This disease has similar symptoms with Flu such as fever, cough, fatigue which are essential to know to diagnose at the early stage [11]. The incubation period of COVID-19 takes from 1 to 14 days. Surprisingly, a patient without any symptoms can possibly be a transmitter of the COVID-19 virus to others. This is when quarantining such people is necessary [12]. Moreover, the recovery period of this disease varies and depends on the patients age, underline condition, etc. but in general it can take between 6 to 41 days [13]. While this disease has a high potential capability to be spread easily in comparison with similar diseases within the coronavirus family, there are many ongoing efforts and researches to mitigate the spread of this virus. In this context, IoT technology has been shown to be a safe and efficient way of dealing with COVID-19 pandemic [14]–[16].
Our goal in this study is to determine the role of IoT-based technologies in facing with COVID-19 and review the state-of-the-art architectures, platforms, applications, and industrial IoT-based solutions combating with COVID-19 in three main phases including early diagnosis, quarantine time, and after recovery. Early detection and diagnosis can lead to lesser infection and as a result, better health services for infected patients [17]. Quarantining confirmed or suspected cases and enforcing lock-downs can also decrease the number of COVID-19 infections by separating infected people or areas from others. Tracking COVID-19 patients after recovery will benefit the monitoring of returning symptoms and the potential infectivity of these recovered cases [18].

The remainder of the paper is organized as follows. Section II covers the importance of IoT during COVID-19. Section III highlights IoT technologies along with their categories for the phase of “Early Diagnosis.” Similarly, Section IV and V review IoT technologies in “Quarantine Time” and “After recovery” phases respectively. IoT-enabled Smart City is discussed in the context of COVID-19 in Section VI. Finally, we discuss, conclude and outline future work in Sections VII and VIII respectively.

II. IMPORTANT ROLE OF IoT IN COVID-19

Since early 2020, the world has been struggling with the COVID-19 pandemic caused by the novel severe respiratory syndrome coronavirus 2 to cure and control the unprecedented spread of the virus. As most of the efforts to find a treatment or control the spread of the COVID-19 have failed so far, there is a high demand for global monitoring of patients with symptomatic and asymptomatic COVID-19 infection.

In recent years, IoT technology is getting significant attention in the healthcare domain where it plays an important role in different phases of various infectious diseases [19]. In the current pandemic, as the contingency of COVID-19 is high, there is an essential need for patients to be connected with and monitored by their physicians proactively in different phases of COVID-19. In this study, we investigate the role of IoT technology in response to COVID-19 in three main phases including early diagnosis, quarantine time, and after recovery.

During the first phase of Covid-19, which is early diagnosis [20], there is an essential need for faster diagnosis due to the high possibility of spreading the virus to others by asymptomatic patients. The sooner the patient is diagnosed, the better the spread of the virus can be controlled, and the patient can receive appropriate treatment. In fact, IoT devices can speed up the detection process by capturing information from the patients. This can be implemented by capturing body temperatures using different devices, taking samples from suspicious cases, and so on.

The second phase, called quarantine time [21], is an important part of this disease when the patient is diagnosed with COVID-19, and he should be isolated for the period of treatment. IoT devices are able to monitor patients remotely [22] with respect to their treatments and stay at home orders by the authorities, and also cleaning areas without human interactions such as the implementation of tracking wearable bands, disinfecting devices, etc.

According to the CDC [23], most people can recover with mild symptoms while staying at home without getting treatments, but there is not a guarantee for reinfection. It might happen with other symptoms of COVID-19 [24]. With respect to these possible reinfections in after recovery phase, the chances of returning symptoms and the potential infectivity can get high [18]. In order to avoid that happen, social distancing should be implemented by deploying IoT devices including bands, crowd monitoring devices, etc. to track and monitor people to ensure the appropriate distance is practicable.

In short, IoT technology during the COVID-19 pandemic has shown its capabilities of assisting patients, healthcare providers, and authorities using various IoT enabled/linked devices including wearables, drones, robots, IoT buttons, and smartphone applications. In this section, we briefly explain the various IoT devices and applications that are mainly utilized in the forefront of combating COVID-19. Table I enlists the specifications of these technologies regarding this pandemic.

A. Wearables

Wearable technologies can be defined as the combination of electronics and computers with anything that is able to be worn. In a similar case, the definition presented by Juniper Research [25] describes it as app-enabled computing technologies that receive and process input while it is either worn or stick to the body such as bands, glasses, watches, etc. These smart wearables were designed for different purposes in various domains such as healthcare, fitness, lifestyle, and so on [25–27]. Although the privacy of data is still a significant issue for expanding these devices, it is predicted that healthcare providers will spend $20 billion annually until 2023 on wearable IoT devices to monitor more patients [28]. IoT wearable devices covers a wide range of different smart wearable tools such as Smart Thermometers [29, 30], Smart Helmets [31], Smart Glasses [32], IoT-Q-Band [33], EasyBand [34], and Proximity Trace [35]. With respect to wearable devices, Table I shows all devices regarding their classification with real-time examples.

B. Drones

Drones are simply aircraft that are flown without any or very less human operation by remote monitoring [36]. In 1849, during a war between Italy and Austria, the first drone, which was a balloon equipped with bombs, was used [37]. The drone is also known as an unmanned aerial vehicle (UAV) that works with the help of sensors, GPS, and communication services. Moreover, the implementation of IoT within drones known as the Internet of Drone Things (IoDT) makes it possible for drones to do a variety of tasks such as searching, monitoring, delivering, etc. [38, 39]. Smart drones can be monitored by a smartphone and a controller with the least time and energy, which makes them efficient in different fields such as agriculture, the military, healthcare, etc.
Different types of IoT-based drones including Thermal Imaging Drone [40], Disinfectant Drone [41], Medical Drone [42], Surveillance Drone [43], Announcement Drone [44], and Multipurpose Drone [45] using in healthcare domain and in particular in COVID-19 will be discussed in this paper. An illustration of these types of drones along their real-time examples can be found in Table [III].

C. Robots

According to the Merriam Webster dictionary [46], a robot is defined as “a machine that resembles a living creature in being capable of moving independently.” As an advancement during the emergence of networked robots within the cloud, the Internet of Robot Things was implemented because they have many advantages by doing different tasks to make life easier [47]. Regarding the current pandemic, robots can be categorized as Autonomous robots [48], Telerobots [49], Collaborative robots [50], and Social robots [51]. Table [V] also displays the fundamentals of these robot types and instances.

D. IoT Buttons

This type of IoT device is a small, programmable button connected to the cloud through wireless communication [52]. Based on its written code on the cloud, this device can be applied to perform different tasks by pressing only one button. It is useful to apply to do repetitive tasks to increase the efficiency of staff. A real-time example of an IoT button is allowing users to complain if any hospital restrooms need cleaning and then receiving a response from housekeeping staff after the restrooms have been cleaned. In this case, the management is able to keep restrooms clean [53]. Table [V] illustrates two implementation of these button during COVID-19 phases.

E. Smartphone Applications

Smartphone applications are application software designed to do limited tasks within a mobile device such as a smartphone [54]. Since there are 3.5 billion active smartphones in 2020, these IoT-based cost-effective smartphone applications could be very efficient in various domains including healthcare, retail, and agriculture by using real-time data [57–60]. A good number of smartphone applications have been developed so far in healthcare area which some of them are utilized in response to COVID-19 illustrated in Table [VI], namely nCapp [61], DetectaChem [62], Stop Corona [63], Social Monitoring [64], Selfie app [65], Civitas [66], StayHomeSafe [67], AarogyaSetu [68], TraceTogether [69], Hamagen [70], Coalition [71], BeAware Bahrain [72], eRouska [73], and Whatsapp [74].

III. PHASE I: EARLY DIAGNOSIS

The key to combating COVID-19 is to diagnose it early to prevent spreading the virus widely. This will substantially help healthcare providers to arrange a better treatment plan, save more lives, and reduce contamination and infections [84]. The first step in early diagnosis in COVID-19 is understanding the symptoms of COVID-19. According to the CDC [11], as of June 26, 2020, COVID-19 has a wide range of symptoms including fever or chills, cough, shortness of breath or difficulty breathing, fatigue, muscle or body aches, headache, the new loss of taste or smell, sore throat, congestion or runny nose, nausea or vomiting, diarrhea. Among them, fever or high body temperature is one of the most common symptoms of COVID-19 when the measured temperature exceeds 38 Degrees Celsius or 100.4 Degrees Fahrenheit [85]. IoT devices can make the detection process more efficient by capturing data within their sensors and then analyzing the data for patients, healthcare providers, and authorities to diagnose, control, and ultimately stop this contagious disease [86]. There are different IoT devices that can be utilized in order to capture some of the aforementioned symptoms at the early stage that will be covered in the next subsections.

A. Wearables

Wearable devices enable an efficient type of measurement in response to the need for early diagnosis by using developed technologies and sensors [87]. Developing these devices has had a remarkable impact on the early detection of diseases. For example, by capturing every single health data from the user, wearable IoT device is capable to show if any of respiratory signs are not normal. Within this knowledge, the user can notice any change in his/her health situation regularly, and then decide to set an appointment before any symptoms appear [76]. With respect to the implementation of smart wearables in the healthcare field, the COVID-19 pandemic might be easier to fight with appropriate wearable devices. Afterward, monitoring patients remotely with the application of sensors would be more convenient [88], [89].

1) Smart Thermometers: A wide range of IoT smart thermometers has been developed to record constant measurements of body temperatures. These low-cost and accurate devices are offered in different types including touch, patch, and radiometric [30]. The use of these devices can be extremely helpful in the early detection of suspicious cases. Also, since the use of infrared thermometers for capturing body temperature can possibly spread the virus more due to the closeness of patient and health experts, using smart thermometers is highly recommended in such cases [40].

According to [90], Kinsa’s thermometers have been widely used in homes, and the company is now able to predict the most suspicious areas in each state of the USA based on the recorded temperature with the high possibility of being contaminated with COVID-19 [29], [91–93]. Additionally, many wearable smart thermometers have been developed such as Tempdrop, Ran’s Night, iFiever, and iSense (shown in Fig. [1]), and they can report the body temperature at any time on a smartphone. These touchable thermometers can be worn or stick to the skin under clothing [50]. Implementing these devices in people’s daily lives can improve the chance of diagnosing new patients.
TABLE I

| Model | Technology Description | Pros | Cons |
|-------|------------------------|------|------|
| Wearables | An app-enabled technology for receiving and processing data that is worn on or stick to the body | • Consistent monitoring<br> • Improving the quality of patient’s medicare<br> • Safer and more efficient hospitals<br> • Lowering hospital visits | • Security and privacy of data<br> • Short battery life |
| Drones | An aircraft equipped with sensors and cameras, GPS and communication systems which is flown with less or no human interactions | • Perform variety of tasks such as (searching, monitoring, delivering)<br> • Reach to hard-to-access locations<br> • Lower the workers’ interactions such as maintaining | • Security issue (large unstructured data)<br> • Quality of Service<br> • Low connections |
| Robots | A programmable machine which can handle complex actions like a living creature | • Lowering interactions by remote diagnosis and treatments<br> • Maintaining such as cleaning and disinfecting | • Bias and Privacy concerns<br> • Reduce mental health problems |
| Smartphone Applications | An application software designed to do limited tasks within a mobile device | • Monitoring and Tracking<br> • Cost-effective | • Collected data privacy and Security |

2) Smart Helmet: Using a wearable smart helmet with a thermal camera has shown acceptable results considering the lower human interactions compared to the infrared thermometer gun [40]. When the high temperature is detected by the thermal camera on the smart helmet, the location and the image of the person’s face are taken by an optical camera and then sent to the assigned mobile device with an alarm as shown in Fig. 2 so that the health officer can distinguish the infected person, and authorities can take action. In this model, while a health officer is capturing the crowd, he/she has access to the temperature, personal information, dark spot visioning, and facial recognition of the people in the crowd. All of the captured data will remain on the helmet [31]. Additionally, Google Location History can be incorporated with the smart helmet to find the places visited by the suspected person after detection [94]. Countries such as China, UAE, and Italy have implemented this wearable device to monitor crowds within two meters from passers-by [95]. Interestingly, this model has shown good results. For example, KC N901 is one of the smart helmets produced by a Chinese company that has an accuracy of 96 percent for high body temperature detection deployed by the above countries [95].

3) Smart Glasses: Another approach is the application of IoT Based Smart Glasses (Fig. 3) which are placed in wearable devices. Smart glasses can be considered as a good replacement for thermometer guns when we are looking for less human interaction. Optical and thermal cameras have been used in smart glasses to monitor the crowds [32]. It has face detection technology at the time of capturing body temperature, which makes tracking easier. It also has the help of Google Location History, which makes the data more reliable. All the captured data will be sent to health officers on a smartphone for further actions [32]. Among different smart glasses, Rokid [96], a Chinese company, has been producing these smart glasses with infrared sensors to combat COVID-19 with the ability to monitor up to 200 people. Another example of these devices is the combination of Vuzix smart glasses with the Onsight Cube thermal camera (see Fig. 4) where these two can also help detect high temperatures and provide real-time information for medical centers [97].

B. Drones

In general, finding infected people in a crowd is a key point in early diagnosis and control COVID-19 [103]. Using Unmanned Ariel Vehicles (UAV) and in particular IoT-based


| Model Type                        | Capability                                                                 | Examples                                         | Phase |
|----------------------------------|---------------------------------------------------------------------------|--------------------------------------------------|-------|
| [29], [30], [40], [92] Smart Thermometers | • Temperature monitoring  
• Increasing the diagnosis rate                                              | Kinsa, Tempdrop, Rans Night iFiever, iSense      | I     |
| [31], [95] Smart Helmet           | • Temperature monitoring  
• Capturing location and face image  
• Less human interactions                                                       | KC N901 in China                                 | I     |
| [32], [96] Smart Glasses          | • Temperature monitoring and capturing  
• Less human interactions                                                       | Rokid in China  
Vuzix & Onsight                                                             | I     |
| [33], [57] IoT-Q-Band             | • Tracking quarantined objects in case of absconding  
• Cost-effective tracking  
• Destructible                                                                 | Hong Kong electronic wristband  
Electronic ankle bracelet in USA                                             | II    |
| [34], [99] EasyBand              | • Monitoring social distancing practice by people  
• Alert the danger of closeness by LED                                           | Pact wristband                                    | III   |
| [35], [100]–[102] Proximity Trace | • Monitoring workers for the social distancing practice  
• Tracing contacts of contaminated employee                                      | Hardhat TraceTag  
Instant Trace                                                                | III   |


C. Robots

Using robots linked with IoT to assist early diagnosis is a remarkable use of these devices because they can help health workers by processing the patients’ treatment and lowering the work stress level [79]. Without the interaction of humans, the Autonomous Robot can help fight in all COVID-19 phases.
TABLE III

| Model          | Type                  | Capability                                      | Examples                                 | Phase     |
|----------------|-----------------------|-------------------------------------------------|------------------------------------------|-----------|
| [40], [104]    | Thermal Imaging Drone | • Temperature capturing in the crowd<br>• Less human interactions | Pandemic Drone                           | I         |
| [104], [108]   | Disinfectant Drone    | • Sterilizing contaminated areas<br>• Preventing health workers from being infected<br>• Less human interactions | DJI                                   | II        |
| [109]–[111]    | Medical/Delivery Drone| • Reducing the hospital visits<br>• Increasing accessibility to treatments | Delivery Drone Canada                   | II, III   |
| [44], [112]    | Surveillance Drone    | • Crowd social distancing monitoring            | MicroMultiCopter Cyient                  | III       |
| [104], [113]   | Announcement Drone    | • Broadcasting information about COVID-19       | Broadcasting drone in Spain and Kuwait   | III       |
| [45]           | Multipurpose Drone    | • Temperature capturing<br>• Disinfecting areas<br>• Crowd monitoring<br>• Broadcasting information | Corona Combat                          | I, II, III|

Within the first phase of pandemic, it can help the process of diagnosis by collecting samples of throat swabs from patients with the advantage of preventing medical staff infection [48]. Fig. 6 depicts how this process works out. An example of this device, the Intelligent Care Robot, has been developed through a partnership between two companies, Vayyar Imaging [114] and Meditemi [115]. This device detects symptoms of this disease in under 10 seconds by touchless quick scanning of a person within a distance of 1 meter to capture respiratory signs and temperature [116]. Regarding the implementation of robots for this pandemic, bias and privacy are the major issues within using the robots during the COVID-19 pandemic. The possibility of making a wrong decision between patients and the security of massive collected data has to be considered [82].

D. IoT Buttons

In order to manage diagnosis better and faster, alerting the authorities or family of the patient about any contaminated area or any emergency can play an important role. In Canada, IoT buttons from Visionstate [123] were deployed for the purpose of cleaning in Canada’s hospitals. They are named Wanda QuickTouch (Fig. 7), which are designed for alerting management in case of any concerns related to essential sanitation or public safety. These buttons can be adhered to all surfaces and located wherever needed. The operation of these buttons is done with a battery and a connection to the LTE-M network [124], which are capable of increasing the detection accuracy [125]–[127].

E. Smartphone Applications

Smartphone applications enabled with IoT using real-time information such as Global Positioning System(GPS), Geographic Information System(GIS), etc., for tracking purposes have been widely applied in order to increase the chance
of detecting infected people. Implementing smartphone applications using the Internet of Medical Things (IoMT) as a platform in healthcare systems could have benefits including receiving treatment from home and having a complete database so that healthcare workers and the government can smoothly monitor the disease. People are able to upload their health information to the cloud adopted by IoT and get health advice from hospitals online. Within this platform, patients will be cured at home without expanding the contamination. It costs less than having a physical appointment at hospitals and allows the government to take better action in order to manage the pandemic in the future. Since starting the pandemic, some smartphone applications have been developed dedicated to COVID-19 diagnosis and monitoring that will be discussed in the coming sections.

1) nCapp: One approach in China is implementing the Internet of Medical Things within a cloud terminal as an application called “COVID-19 Intelligent Diagnosis and Treatment Assistant Program (nCapp).” This cellphone application based on an automated diagnostic system is straightforward because of the menu page with all its eight functions that can be selected by the user. nCapp can automatically generate the diagnosis for the patient based on requested data and questionnaire submitted by the user. Diagnosis is categorized into three cases including confirmed, suspected, or suspicious. For the confirmed cases, there are four conditions including mild, moderate, severe, and critical, which are determined by the physician. Special treatments for these conditions and other types of cases are defined as well. Other positive points of this program are included updating its own database in order to improve its diagnosis, giving the ability of consultation for all health workers, making sure all patients are safe in long term, and finally, having all these abilities available on a worldwide scale. Altogether, diagnosis is possible sooner, and the spread of disease can be controlled much better, especially by physicians.

2) MobileDetect: The need to develop a process of identifying infected people has led DetectaChem to develop a low-cost COVID-19 test to beat the spread of this pandemic. The important point of this test is the compatibility with a smartphone application named MobileDetect, with which users can easily take the test at home using a sample from a nasal swab. After the accurate result shows up on the smartphone application within 10-30 minutes, the user is able to report the result with any additional information needed such as picture, location etc.. Also, communicating with healthcare centers about further action is available for users. This smartphone testing kit authorized by the Food and Drug Administration (FDA) can be helpful during the first phase of pandemic and then lower the spread of the virus.

3) Stop Corona: Besides all the implementations for early case detection, building a database by capturing daily health report including contact with others, symptoms, and location. The Stop Corona application runs on the web through any mobile devices that provide a heatmap based on the disease spots. It also can increase the chance of early detection for outbreaks with the use of captured information.

**IV. Phase II: Quarantine Time**

After the process of detection, there is a necessity for isolating and then monitoring the patient either in a hospital or home. The quarantine does not only apply to the confirmed cases but also can be applied to different areas or cities or even countries, which is known as a lockdown. Additionally, this objective is set to prevent the possible transmission from suspected cases (asymptomatic cases) to others. With respect to main challenges during quarantine time, including providing food and treatment, IoT devices could help ease these issues. Additionally, they are implemented to efficiently monitor patients and control their respiratory signs including heart rate, blood pressure, and so on.

**A. Wearables**

The importance of quarantine time for a confirmed or suspected case is vital because there is a chance of spreading the virus to other people. In order to prevent absconding from the quarantined area, a wearable band called IoT-Q-Band is designed within IoT applications. With respect to the...
TABLE V

| Model | Type | Capability | Example | Phase |
|-------|------|------------|---------|-------|
| [123], [125]–[127] (1) | • Alerting the authorities or family | Wanda QuickTouch | I |
| [128] (2) | • Alerting healthcare provider in case of an emergency | Sefucy | II |

As the pandemic moves into the quarantine period, the world is facing a large number of deaths due to COVID-19. Also, as a result of having close contact with patients or the essential need for sterilization (which puts maintenance workers in a contaminated area), many health workers are exposed to this virus [136]. The use of drones can be very important during the quarantine time to decrease the number of active cases by lowering the interaction of workers within contaminated areas. Drones can assist humans by disinfecting areas or delivering medical treatments to patients.

1) Disinfectant Drone: Keeping areas sanitized and disinfected during the quarantine period is very important and this can be achieved by using another type of drone, called Disinfectant Drone [108] (See Fig. 9). These types of drones are capable of reducing the contamination of the virus and also preventing health workers from getting infected. DJI, a company in China, made these drones with the ability to disinfect one hundred meters in one hour. It was also employed in Spain for disinfecting purposes [104].

2) Medical/Delivery Drone: The use of this drone for the very first period of COVID-19 is to commute without any human interactions between labs and medical centers to deliver the COVID-19 test kits and samples or medical supplies that increase the speed of diagnosis by cutting delivery time, as it was done in Ghana and China [109], [148]. This drone is another technology for reducing hospital visits and increasing access to medicare by delivering medical treatments rapidly. It could be either to a patient or to another medical center. This type of drone can be specifically used while COVID-19 confirmed cases are isolated in their homes during a quarantine time [110]. Fig. 10 illustrates a picture of this type of drones. This drone can also be used for post and grocery services which would benefit the practice of social distancing as the stores are opening because of avoiding unnecessary physical contacts in the public while they can receive their goods by the drone without any contact with others [149]. A real-time delivery drone during COVID-19 is Delivery Drone Canada which can move COVID-related goods including test kits, swab tests [111].

Fig. 9. Disinfectant Drone [137].
### TABLE VI
**IoT enabled/linked smartphone applications during COVID-19**

| Model | Application | Function | Phase | Origin | IOS | Android | Web |
|-------|-------------|----------|-------|--------|-----|---------|-----|
| 61    | nCapp      | • Keeps database updated  
• Provide available consulting  
• Controlling patients health in long-term | I   | China  | –   | –       | –   |
| 62    | DetectaChem | • Taking COVID-19 low-cost tests within a kit joined with a smartphone application | I   | USA    | ✓   | ✓       | –   |
| 63    | Stop Corona | • Getting daily health reports including contact, symptoms and location  
• Building a map with high risk spots | I   | Croatia | –   | –       | ✓   |
| 64    | Social Monitoring | • Track patients with the diagnose of COVID-19  
• Access to the user’s information by government (privacy concern) | II  | Russia  | ✓   | –       | –   |
| 65    | Selfie app  | • Monitoring patients by asking randomly to send selfies | II  | Poland  | ✓   | ✓       | –   |
| 66    | Civitas     | • Determining perfect time for suspected cases to leave for essentials | II  | Canada  | –   | –       | ✓   |
| 67    | StayHomeSafe | • Monitoring arrivals at the airport with use of smartphone application and a wristband | II  | Hong Kong | ✓   | ✓       | –   |
| 68    | AarogyaSetu | • Linking people and health services better | III | India   | ✓   | ✓       | –   |
| 69    | TraceTogether | • Capturing the people who were close to the user with encrypted IDs  
• Accessing to the user’s information by government (privacy concern)  
• Notifying people who were in close contact with user if user is infected | III | Singapore | ✓   | ✓       | –   |
| 70    | Hamagen     | • Finding out if the user has been in a close contact with a positive tested for COVID-19 | III | Israel  | ✓   | ✓       | –   |
| 71    | Coalition   | • Securely notifying about detected cases who users have been in contact with   
• Location services must be ON | III | USA     | ✓   | ✓       | –   |
| 72    | BeAware Bahrain | • Alerting people with close contact of infected person  
• Track the self-isolated people  
• Location services must be ON | III | Bahrain | ✓   | ✓       | –   |
| 73    | eRouska(smart quarentine) | • Capturing physical contacts between user and people | III | Czech Republic | ✓   | ✓       | –   |
| 74    | Whatsapp    | • Provide healthcare support without visiting hospital  
• Available consulting with the physician | I, II, III | Singapore | –   | –       | ✓   |

which helps move the robot. These robots can sterilize the place that had interactions with patients. A real-time example of this device is the daVinci surgical robots which are operated by a physician while the patient is in the safe isolation of plastic sheeting. Fig. 11 shows the actual daVinci telerobot. This helps to prevent infections by remotely doing surgeries [49], [119].

C. Robots

During quarantine time, robots play an important role in keeping medical staff away from isolated patients. Consequently, medical workers will not be infected by having close contact with patients [150]. Robots can be used in different ways such as capturing respiratory signs and providing assistance to patients with their treatments or food.

1) Telerobots: During a quarantine time, telerobots operated remotely by a human can allow remote diagnosis, surgeries, and treatments for the patients while there is no human interaction during the process. For example, a nurse can measure patients’ temperatures without having interactions with them by using these robots and their mobile manipulators, which helps move the robot. These robots can sterilize the place that had interactions with patients. A real-time example of this device is the daVinci surgical robots which are operated by a physician while the patient is in the safe isolation of plastic sheeting. Fig. 11 shows the actual daVinci telerobot. This helps to prevent infections by remotely doing surgeries [49], [119].

2) Collaborative Robots: Unlike telerobots in the previous section, Collaborative Robots known also as Cobots are
best to use if there is a need for an operation performed by humans. They are not as beneficial as telerobots for this pandemic, but during a quarantine, this type of robot can lower healthcare workers’ fatigue as well as track their interactions with patients [49]. For instance, Asimov Robotics in India is designed for a quarantine time to help patients in isolated areas with tasks such as preparing food and providing medication and also preventing healthcare workers from being in that area [50], [120]. (Fig. 12) Another example of this robot during this phase is using the eXtremeDisinfection robot (XDBOT) (shown in Fig. 13) in Singapore which is programmed by Nanyang Technological University. This robot can disinfectant hard-accessible areas such as under the bed, and also can be wirelessly operated on a mobile platform which can be a smartphone, tablet, or even a laptop which avoids any close contact between humans and the contaminated areas [121], [152].

3) Autonomous Robots: Autonomous Robots have also been used during quarantines time. They work with fewer or no human interactions and can be utilized in many cases with the use of wheeled mobile robots to sterilizing contaminated places in hospitals, carrying patients’ treatments, and checking their respiratory signs, which all will decrease the risk of infection for the healthcare workers while the patients are isolated in their rooms. Also, all these processes can be done without any contact between patient and healthcare worker [49], [118]. For example, the disinfection robot created by Xenex [80] is capable of cleaning and disinfecting areas of viruses and bacteria. Fig. 14 illustrates the Xenex robot breaks down the virus using UV lights. Additionally, UVD robots developed by a Danish company are used for disinfecting hospitals with their strong UV light, which destroys the DNA of the virus [81].

4) Social Robots: According to the CDC [155], isolation and quarantine patients can potentially cause mental health problems as well. To prevent this, Social Robots are designed for communicating with patients during that time. The functionality of these robots in this pandemic is to help reduce the mental fatigue and strain during a quarantine time and period of physical distancing [49]. One example of these robots is Paro [51], which can help patients during their isolation as a stress-relief device as it is shown in Fig. 15.
D. IoT Button

The use of the IoT button in response to the COVID-19 pandemic can help to track during the quarantine phase. The Sefucy IoT button [28] was originally designed for tracking lost or missing children, but with the outbreak of COVID-19, this IoT device has been used in other ways. If the health condition of a confirmed case isolated at home gets worse, by pressing the button, a healthcare provider will be alerted or family members will be notified in case of an emergency. Also, an instant nurse call from the patient can be included. Emergency notifications during a quarantine is an important function of this device because it does not require close physical contact.

E. Smartphone Applications

The most critical part of quarantine is keeping track of patients while they are isolated. Tracking using smartphones during quarantines has also been widely developed.

1) Social Monitoring: In Russia, a surveillance mandatory application called Social Monitoring [64] has been developed by government to track patients who are diagnosed with COVID-19 and have to be isolated in their homes within the functionality of geofencing. Authorities can track the patient after the application is installed. In addition, people need to request a QR(Quick Response) code every time they want to leave home in order to present it to the police. There is also privacy concern because of the access of government to all those information [132], [138], [139].

2) Selfie app: This application was developed in Poland to track patients who have been told to stay at home for 14 days. Patients can reject installing this application, but in return they will get unexpected visits from authorities. Otherwise, they will be asked to send selfies randomly during the day. Geo-location and facial recognition have been used to make sure they are staying at home [65], [140], [141].

3) Civitas: A Canadian application has been progressed to lower the COVID-19’s impact. With the use of the user’s identification, this application communicates with the authorities to request and receive a permit that allows the user to leave the house. It is because of the importance of keeping people away from contaminated areas. Also, it assists suspected cases who need to go outside for buying essential goods in a perfect timely manner. Furthermore, it allows doctors to contact patients to monitor their health status and give advice if needed [66], [142].

4) StayHomeSafe: Moreover, the combination of smartphone applications and wearables have been used in Hong Kong. These are the StayHomeSafe application [67] and a wristband. Quarantine arrivals at the airport will be given a wristband that has a specific QR code. Then, whenever the users arrive at home, they can pair both application and wristband together in a short time in order to set the quarantine location with the advantage of geofencing technology used by the application [132].

V. Phase III: After Recovery

Governments tried closing marketplaces and businesses in order to decrease the contamination, but many jobs have been lost and economic problems created. In order to deal with this, they decided to gradually reopen businesses that can be placed in the After Recovery phase of COVID-19. Meanwhile, an effective solution, social distancing, has been implemented to make sure the virus will not spread again [156].

A. Wearables

Since employers are gradually bringing workers back to the workplace, there should be some protections in order to keep them safe from this virus. Two approaches of Contact Tracing and Social Distancing need to met by developing wearable devices in order to trace users’ close contact with any other people and also alert them as the social distancing is not performed [157].

1) EasyBand: As countries gradually reopen the jobs and marketplaces after the lock-down, EasyBand is one of the best IoT approaches that make sure people are practicing social distancing. This wearable device using the Internet of Medical Things (IoMT) is used by sensing and capturing data from other devices. EasyBand [34] works within a specific radius and shows potential danger by its LED lights. These bands vary from person to person depending on how close they got to other people. For instance, if someone with a red light gets close to someone else less than 4 meters, the second persons EasyBand starts beeping to alert about the chance of contamination so that its user can stay away. This device is also much better than smartphones because 1. There is no need for smartphone operation. 2. It is useful as a road pass for detecting suspected cases as they leave the city. 3. It is much cheaper than smartphones. 4. It gives people more safety and peace. Fig. 16 represents the process of the workflow of this wearable. A similar real-time example for this device is the use of Pact wristband [99](see Fig. 17), which alerts at the of close contact by vibrator and buzzer.

Moreover, the combination of smartphone applications and wearables have been used in Hong Kong where the StayHomeSafe application [67] and a wristband work together in order to make sure that new arrivals at the airport will be self-
quarantine for a period of time using application and wristband [132].

![Pact wristband for alerting and tracing](image1.png)

**Fig. 17.** Pact wristband for alerting and tracing [99].

2) **Proximity Trace:** As industrial workers are coming back to work after the lockdown, there is an essential need for practicing social distancing between them while they work together. Proximity Trace [35] helps industrial workers maintain social distancing in practical ways. This device, which can be worn on a hard hat or the body, alerts workers when they get close to each other with a loud sound. Using this device, instead of worrying about contamination from the virus, workers will be able to concentrate on their work. Fig. [18] displays how this trace can stick to the industrial workers’ hard hat. Also, Instant Trace, shown in Fig. [19] does the same at a workplace developed within a badge of employee which helps to maintain the social distancing and tracing the infected employee’s contacts [102].

![Instant Trace worn as badge in workplace](image2.png)

**Fig. 19.** Instant Trace worn as badge in workplace [35].

![Surveillance Drone](image3.png)

**Fig. 20.** Surveillance Drone [159].

**B. Drones**

As the pandemic enters the After Recovery phase, many drones have been used in response to the reopening which assists businesses to continue working in a safe manner. Increasing social awareness by monitoring the crowds and broadcasting information is the main purpose of implementing these devices during this phase [158].

1) **Surveillance Drone:** Governments have been trying to establish a way of monitoring a crowd in case of people’s failure to do social distancing. The Surveillance Drone can control a crowd. Two examples of this type of drone can be found in China and India. They are made by MicroMultiCopter(China) [44] and Cyient(India) [112]. Fig. [20] displays a model of this type. The MicroMultiCopter drone has also been equipped with speakers to announce important information from the government which will be discussed in the next type of drone within this phase.

2) **Announcement Drone:** This type of drone is mainly designed for broadcasting in areas with low accessibility to the Internet. The use of this drone by the authorities in Spain and other European countries to announce the practice of social distancing and other guidelines with loudspeakers is an example of this type of drone’s role after the re-openings [104], [113]. Broadcasting “go home” messages with this drone to people in crowds has been done in Spain, Kuwait [149] (see Fig. [21]).

![Surveillance Drone](image4.png)

**Fig. 18.** Use of TraceTag on a hard hat [35].

![Surveillance Drone](image5.png)

**Fig. 19.** Instant Trace worn as badge in workplace [35].
3) **Multipurpose Drone:** Lastly, a Multipurpose Drone, called Corona Combat [45], has been implemented in China with the combination of all other types of drones which can do all of the proposed goals mentioned in three phases at once. This drone can be deployed in any COVID-19 phases. Fig. 22 shows this drone with all the facilities from other drones.

### C. Robots

People usually prefer to interact with humans, not robots. But after spreading of COVID-19 all over the world, many of their preferences changed. As the pandemic enters the third phase, the need for social distancing has to be met by lowering the number of workers [160]. In response to this phase of COVID-19, the Autonomous robot can be used after recovery to control social distancing. For instance, Spot [161], a four-legged robot designed in Singapore to be similar to a dog, reminds people to practice social distancing in the park by barking orders if they do not stay the appropriate distance apart. While this robot can be controlled remotely, it is also capable of transferring data to a web interface for further monitoring. [162]. Fig. 23 is the Spot robot for monitoring the practice of social distancing.

### D. Smartphone Applications

The use of IoT in healthcare is now expanding, and the major benefits are cost-effectiveness, efficient monitoring, appropriate treatment, fewer mistakes, and exceptional diagnoses. Some smartphone applications have been developed specifically in response to the pandemics challenges.

1) **AarogyaSetu:** India designed a contact tracing application named ArogyaSetu [143], [144] for people to use on their smartphones to increase awareness of and fight against this virus. ArogyaSetu is designed for a better connection between health services and people. The user will be asked if he/she has any symptoms of COVID-19 or has recently traveled internationally. It also notifies the user if he/she has had contact with someone who is already or later becomes a confirmed case. The government of India confirmed that the data caught by GPS will not be used for any other purposes [15].

2) **TraceTogether:** Singapore launched an application called TraceTogether [69] to capture data using an encrypted ID from people who were in close contact with each other. It will store the duration of the visit and the distance between them for 21 days. Users have to allow the app to have their phone number, and the captured data will not be used until a close contact identification is established [145], [164].

3) **Hamagen:** This contact tracing application was developed in Israel. It uses GPS to find out if the user has been in close contact with a person who tested positive for COVID-19. Private data from users will not leave the phone until the user agrees on [70].

4) **Coalition:** An application called Coalition [71] within the IoT using blockchain [165]–[168] platform allows contact tracing in a secure way because users have random IDs so that with the detection of any new cases, the users who were in close contact with those cases will be notified.

5) **BeAware Bahrain:** The government in Bahrain developed a contact tracing application that alerts people when they are approaching a contaminated area with a detected COVID-19 case or if they were in close contact with a confirmed case. Also, this application monitors the location of self-isolated cases for 14 days and allows users to book an exit time from isolation for the testing appointment which is useful in the second phase of this pandemic [72], [146].

6) **eRouska:** Similar to other tracing applications during the After Recovery phase, this application also captures the people
whom users had close contact with or let people know if the user is tested positive for COVID-19. The use of Bluetooth whom users had close contact with or let people know if the user is tested positive for COVID-19. The use of Bluetooth because the data is different from one patient to another [15].

7) Whatsapp: As of April 2020, the world has about 3.8 billion users on social media [169]. This amount of users is a great opportunity to implement telemedicine healthcare support using social media applications during this pandemic. With the use of Whatsapp, the patient can easily consult with a physician using virtual meetings without any contact with other people. Then, hospital visits will be also decreased. Using this method is applicable to all phases during the COVID-19 [170].

Of all these applications, IoT is most likely to be able to manage the pandemic. Its services can be used by patients in order to capture their vital signs. It also monitors peoples health situations. Most importantly, it handles the treatment of cases by monitoring patients’ location. Security of captured data is the most important issue with implementing the IoT because the data is different from one patient to another [15].

VI. IOT-ENABLED SMART CITY DURING COVID-19

The term “Smart City” was first coined by IBM and CISCO with respect to the purpose of idealizing a city by connecting all the elements together [171]. Smart City can be characterized by the implementation of different information and communication technologies (ICT), which make devices more connected, and consequently, the city will be more efficiently operated. The quality of living and work environments will also be improved [172]. On the other hand, having a Smart City is subjected to have all the areas monitored which would be tough to reach at this moment due to the absence of infrastructure and network connections. There are lots of efforts behind the scene by incorporating different technologies such as IoT, AI, 5G networks in order to achieve a highly advanced level in different areas of a Smart City. In the healthcare domain, responding to real-time sensed data helps healthcare systems be smarter which means smart city services are enabled to respond promptly to urgent health needs and different health pandemic.

Having a Smart City can be extremely helpful in combating this pandemic through collaboration between medical centers, cities, etc. [173]. Implementation of IoT-enabled Smart City is one of the most important approaches in response to the current epidemic. Along with discussed IoT applications above, Allam et al. [174] highlight the importance of the concept of Smart City Network while the world is struggling with the COVID-19 pandemic. Collected data from smart sensors in IoT Networks and the implementation of AI applied in different places (mostly airports and marketplaces) can help fight against the current and also future pandemic. Sharing databases and standardizing the process can lead to security and privacy issues that need to be resolved with the use of appropriate protocols [175]. In short, the more connections adopted by Smart City technology, the more efficiently the world can deal with such pandemics [174]. Smart City infrastructure can also help people maintain social distancing by the implementation of transportation system technologies including crowd monitoring, smart parking, and traffic re-routing [176]. The following are examples of Smart City devices to deliver better health care services. Pulse Oximeter [177] is able to measure blood oxygen saturation. It can be used to check the lungs, which is helpful for COVID-19 patients by determining whether treatments are working or not during the quarantine of the patients [178], [179]. Similarly, a telemedicine approach for capturing respiratory signs at home is using an electronic stethoscope called eKuore [180]. It is helpful for preventing unnecessary visits to the hospital during the pandemic. It can send lung sounds remotely to a physician, which helps the physician to take care of the patient without being infected or using a mask or face shield. The telemedicine approach by itself has not been able to deal with the patients because of the high number of requests from patients. The practice of monitoring patients remotely using IoT is known as e-health. IoT Telemedicine allows all conversations to be virtual to serve patients better. This can be done with either a website chatbot or smartphone application. In addition, this will prevent healthcare staff from repeating the same information for each patient. Similarly, Providence Health and Services placed their website chatbot and smartphone applications on both Android and IOS platforms. In Japan, a chatbot named BeBot was developed using AI within a mobile application to help patients with their questions [15], [181]– [183]. As a part of smart living in the Smart City, smart home IOT-based technologies can also lower the infection rate of COVID-19. For instance, Smart home doorbells and security systems can be implemented for preventing users from touching surfaces so that there will not be any contamination of the virus by touching those kinds of surfaces [15], [184], [185].

VII. DISCUSSION AND FUTURE WORK

The IoT Polymerase Chain Reaction (PCR) device [186] was developed in 2019 for detecting infectious diseases quickly and helping to prevent pandemics. As the world faces the COVID-19 pandemic, the use of this IoT PCR device, which is connected via Bluetooth to an Android smartphone, can be assumed as an approach of IoT technologies to combating COVID-19. The issue with the PCR test is that it is not 100% accurate when the test result is negative. For instance, if someone tests negative for the disease, this does not prove he is not exposed to the virus [187]. Therefore, the accuracy of this device needs to be improved for better efficiency. The other considerable part is the importance of accurate data that helps speed up the findings of this disease. Consequently, to respond better to this situation and also future pandemics, there is an essential need for more evidence and data from all over the world, and knowledge about solutions each country or even city has found during this pandemic [188]. In addition to the detection process, future works should focus on simulator devices for capturing the possible signs and
an application implemented by Artificial Intelligence called AI4COVID-19 [189] monitors cough for possible contaminated cases. Regarding quarantines, further research needs to be investigated on the intention of people who test positive for COVID-19 but refuse to remain in isolation [33]. More secure devices need to help authorities monitor compliance by isolated patients. Privacy concerns while the government has access to all the information used for monitoring in the periods of the pandemic is a crucial topic. In the long run, after the outbreak is over, it should be determined what will be done with the data collected from people [190]. Since privacy is the most important issue for implementing IoT devices to capture data from people, considering getting paid by governments might be necessary for people to allow authorities accessing their information. Other possible research could be conducted on the use of IoT devices to provide accurate information to prevent fake news. They contribute to peoples stress during a pandemic. Regarding the quarantine phase, one of the major problems with self-quarantine is that the respiration rate can deteriorate quickly. Other implemented wearable devices can be used for this purpose. For example, chest bands using strain gauge sensors [191], and facial masks operating by humidity sensors [192], and flexible patch working [193] with strain sensors can be assigned for respiration monitoring during the quarantine. Another area of study is the impact of working from home, which can be divided into schools and universities, industrial jobs, and so forth. Consequently, the efficient use of IoT devices to improve the quality of working virtually needs to be considered. It is also necessary to implement more accurate technologies for better data collection and analysis with respect to covering all types of people in different jobs or workplaces. Lastly, empowering technologies can play an important role to fight against COVID-19. Use of touchless technology with the help of commands (such as gesture, and voice) will be effective to efficiently lower the spread of the disease and end the pandemic sooner [194].

VIII. CONCLUSION

Internet of Things (IoT) technology has been widely used in various fields. In particular, IoT can perform monitoring, tracking, maintaining, delivering, and collecting information from users to perform additional assistance to healthcare. This technology can help humans to better deal with COVID-19 and future pandemics. There are three phases during this pandemic that need to be considered including “Early Diagnosis”, “Quarantine Time”, and “After Recovery.” In this paper, a comprehensive review of the IoT-related technologies and their devices were discussed based on the COVID-19 phases. In each phase, the reviewed IoT enabled/linked technologies included Wearables, Drones, Robots, IoT buttons, and Smartphone Applications. This paper also discussed the potential applications of Smart City based on IoT in healthcare to lower the impact of COVID-19. The efficiency of this technology varies on the connected devices together, but it has also its privacy issues because of the unstructured captured data from different devices. For example, as a part of Smart City, touchless applications of smart homes can prevent people from infection during this pandemic. In general, the concept of Smart City could be a great tool to fight COVID-19.

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