Journal of Computer Science

Original Research Paper

COVID-19 in the Era of Artificial Intelligence: Existing Technologies and A Strategic Model for Mitigating Future Pandemics

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Article history
Received: 20-10-2023
Revised: 20-11-2023
Accepted: 01-01-2024

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Abstract: Pandemics have existed since the existence of life and will continue as life continues. Throughout many of the previous pandemics, what played a major role in decreasing their severity is how we mitigated and controlled them. The main reason for this is the time it takes for treatments and vaccinations to be developed, which usually takes a long time. Therefore, the techniques used to control a pandemic rapidly change over the course of the pandemic until a cure or vaccine comes to light. At present, emerging technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), fifth generation networks and big data) can have a significant impact on controlling upcoming pandemics including. This study provides a comprehensive survey of current technologies that use AI and big data analytics to take part in the fight against the current pandemic (COVID-19), including their objectives, strengths, weaknesses and challenges. This study also studies existing telemedicine technologies and contact tracing tools used in various countries, which governments have adapted to fight against the current COVID-19 pandemic. This study concludes by suggesting a novel strategic model for controlling and mitigating pandemic crises (e.g., COVID-19). This model represents a guided solution for identifying pandemics and for controlling them using advanced digital solutions from the early stages. More precisely, it can assist in identifying which AI tools can be developed in order to predict pandemics before their outbreaks.

Keywords: COVID-19, Artificial Intelligence, Big Data, Telemedicine Technologies, Contact Tracing Tools

Introduction

COVID-19 was declared a global pandemic by the World Health Organization (WHO) on 11 March 2020 (Cucinotta and Vanelli, 2020). Since the outbreak of this pandemic, it was clear that there was a major urgency for putting strategies in place that were capable of containing and mitigating this pandemic (Heo *et al*., 2020). It was necessary to distinguish between strategies which contain (delay) the pandemic and those which mitigate it. The WHO is related to containing a pandemic by applying procedures to delay the spread of the infection, while mitigating a pandemic is related to minimizing the impact health pandemics should be a top priority (Ferguson *et al*., 2006).

It is also necessary to consider the applicability and effectiveness of any strategy that is defined to control pandemic outbreaks (Ferguson *et al*., 2006; Nicoll and Coulombier, 2009). Countries that use public health measures that strongly rely on preventing, detecting and responding to outbreaks are more likely to mitigate such outbreaks (Kandel *et al*., 2020). One important factor in this regard is to learn from previous pandemics and strategies which help in some way to mitigate them. For example, it can be learned from the influenza pandemic in the US from 1918-1920 that protective sequestration can be very helpful if applied from an early stage of the pandemic (Markel *et al*., 2006).

Classical infection-control methods which were commonly used during many health crises in the past such as extreme quarantine and lockdowns may not be effective for a pandemic that has a scale similar to

COVID-19 (Ting *et al*., 2020). The current advancement in emerging technologies which many organizations have invested in within the healthcare industry can play a major role in remediating the outbreaks of future pandemics similar to COVID-19. These technologies, which could be used to tackle many health problems and diseases, are mainly classified into four domains: The Internet of Things (IoT), big data analytics, Artificial Intelligence (AI) and blockchain technology (Ting *et al*., 2020).

Strategies which rely on digital technologies to mitigate pandemics could indeed provide significant solutions to relieve and minimize pressure on hospitals during this tough time (Moro Visconti and Morea, 2020). A major benefit of implementing digital technologies during pandemics is to minimize the exposure of health workers to infected patients. This definitely would reduce the chance of health workers being infected, leading to more health workers being able to help during the pandemic (Mammoser, 2020). Countries vary in the type of strategy used to control the COVID-19 pandemic; however, many of the countries that have managed to keep low confirmed cases have primarily relied on a strategy consisting of four main elements in Fig. 1 (Whitelaw *et al*., 2020). These elements can be described as conducting early surveillance, testing as many people as possible, tracing the contacts of confirmed cases and applying strict quarantine (Whitelaw *et al*., 2020). Another approach which outlines how technologies were adapted to control the transmission of COVID-19 is (Golinelli *et al*., 2020b). It consists of seven domains in Fig. 2 (i.e., diagnosis, surveillance, prevention, adherence, treatment, lifestyle and patient engagement) (Golinelli *et al*., 2020b).

The work of Alwashi showed that technologies which were implemented in the fight against COVID-19 are related to surveillance, screening, diagnosis, triage, contact tracing and monitoring (Alwashmi, 2020). However, these technologies are faced with a number of challenges that might affect their applicability, such as the lack of accessibility of modern technological devices, capable infrastructure to support advanced technologies and people's acceptance of these technologies (Alwashmi, 2020). In fact, the digital technologies developed in some countries proved to be major enabler for having an effective strategy during the pandemic (Heo *et al*., 2020). On the other hand, digital tools developed in others were not that effective and did not provide the expected results (Pollock *et al*., 2020). Hence, it is essential for any technological tool developed for similar purposes to be capable of learning from the COVID-19 pandemic lessons and it follows a certain model that identifies which AI tools can be utilized in order to predict pandemics from early stages before their outbreaks.

Fig. 1: The four domain strategy to control COVID-19

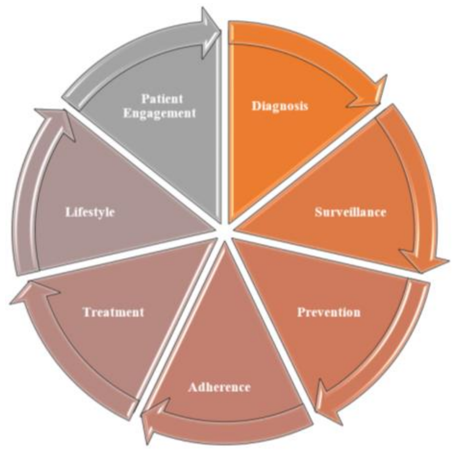

Fig. 2: The seven domain strategy to control COVID-19

Many of existing review papers in literature focus on surveying AI-developed solutions for mitigating COVID-19 from three major categories; prevention, detection and responding. However, none of the existing studies in literature surveyed the potential of predicting a pandemic or a health crisis before its breakout with the assistance of artificial intelligence technologies. This study outlines this gap as shown on Table 1 and defines an AI-enhanced model for predicting future pandemics. Below is a summary of the contributions of this study:

- First, this study illustrates in more details how big data and AI technologies are used in the fight against COVID-19. This is gives a clear identification that such technologies will be sufficient and effective in helping manage the COVID-19 pandemic
- Second, it gives a broader outline of the most effective and promising AI tools either for the prognosis, diagnosis, or treatment of COVID-19. It also shows the latest developments and strategies in various countries with regard to the adaptation of AI telemedicine and contact tracing tools for mitigating COVID-19
- Third, it gives a detailed explanation of the common challenges associated with AI technologies developed for the fight against COVID-19 extracted from experiences on deploying these tools

- Fourth, this study concludes by illustrating the strategic model developed for mitigating future pandemics based on lessons learned from the COVID-19 pandemic. This strategic model identifies which AI tools can be developed in order to predict pandemics from early stages before their outbreaks

Big Data and Artificial Intelligence in the Fight Against the COVID-19 Pandemic

Big data is becoming a promising driver for increasing productivity and supporting innovation in various areas (Wu *et al*., 2016). An earlier comprehensive study in this regard has shown that big data can provide a great assistant in advancing technologies specially when combined with artificial intelligence techniques such as machine learning (Atat *et al*., 2018). In fact, big data would even play a major role in the areas covered by the UN 2030 sustainable development goals (such as healthcare) as shown in the work of Wu *et al*. (2018).

Health data which are generated at a massive amount from various types of resources but their characteristics require more understanding of the nature of such data (Shilo *et al*., 2020). Therefore, big data can be used in many areas of applications in order to contain the COVID-19 pandemic (Pham *et al*., 2020; Mehta and Shukla, 2022). In a report published by WIRED (NIILER, 2020), it was reported that a Toronto-based company which uses big data analytics and specializes in the surveillance of infectious diseases had noticed cases of unusual pneumonia in Wuhan. This allowed the company to warn its client of a possible infectious disease outbreak within that region as early as 31 December (NIILER, 2020).

Table 1: Research reviews on technologies used to tackle COVID-19

Study	AI technologies domains			
	Prevention	Detection	Responding	Prediction
Alwashmi (2020)	✓	✓	X	X
Peng *et al*. (2022)	✓	✓	✓	X
Golinelli *et al*. (2020b)	✓	✓	✓	X
Dogan *et al*. (2021)	✓	✓	✓	X
Khan *et al*. (2021a)	X	✓	✓	X
Syeda *et al*. (2021)	X	✓	X	X
Bhargava and Bansal (2021)	✓	✓	X	X
Musulin *et al*. (2021)	X	✓	X	X
Huang *et al*. (2021)	X	✓	X	X
Zhao *et al*. (2022)	✓	✓	X	X
Mondal *et al*. (2021)	X	✓	X	X
Adamidi *et al*. (2021)	✓	✓	X	X
Fuhrman *et al*. (2022)	X	✓	X	X
Subramanian *et al*. (2022)	X	✓	X	X
Panchal and Sharma (2022)	✓	✓	✓	X

In fact, data timeliness can play a major role in mitigating the outbreak of many pandemics including COVID-19. In the case of pandemics outbreaks, data timeliness can have a great impact on responding and applying control measures (Lawpoolsri *et al*., 2018). Data timeliness is defined by the time taken from diagnosing the first incident of a specific illness to the time when it is recorded (Iqbal *et al*., 2012). A recent study conducted in England has shown that processing data with minimal delays in timeliness can provide better guidance in mitigating COVID-19 (Clare *et al*., 2021). In terms of the effectiveness of artificial intelligence in processing data with a timely response, it has shown that AI-based tools can help medical staff in accurately screening patients with COVID-19, which eventually leads to timely responses in mitigating the spread of COVID-19 (Khan *et al*., 2021a-b).

A recent study by Bragazzi *et al*. has shown various applications for which big data can play a major role during the COVID-19 pandemic (Bragazzi *et al*., 2020). They classified these applications into three categories consisting of: Short-term applications, medium-term applications and long-term applications. Each of these categories has illustrated several applications which can be used to control COVID-19. An example of a short-term application is using big data to help with developing applications for tracking COVID-19 cases, whereas building smart health cities is an example of a long-term application (Bragazzi *et al*., 2020).

Wang *et al*. (2020a); China Inn (2020) are examples of countries that have used big data and data analytics in their favor for controlling the COVID-19 pandemic. Due to Taiwan's previous experience in containing the 2003 SARS epidemic, it was able to establish a comprehensive strategy that relies on big data analytics to control this new pandemic (Wang *et al*., 2020a). China has also made use of big data for the purpose of the prevention and control of COVID-19 (Wu *et al*., 2020a). This is also the case in many countries during this pandemic including efforts by Saudi Arabia Alsunaidi *et al*. (2021), Australia Prentice *et al*. (2020), Canada Leung *et al*. (2020), Japan Konishi *et al*. (2021), New Zealand Summers *et al*. (2020) and many other countries. Furthermore, big data can also have roles in further objectives even after COVID-19. For instance, a study conducted by Sung *et al*. (2021) aimed to use big data and analytics to study the behavior of South Korean tourists after COVID-19.

Some techniques used for this goal include tracking the flow of populations such as the methodology used by Jia *et al*. (2020). This method is designed to use data from over 11 million mobile phones in China. It initially identifies the distribution of confirmed cases in a specific area, thus identifying those areas which might be at a higher risk of COVID-19 distribution (Jia *et al*., 2020). Similarly, the study of (Kraemer *et al*., 2020) studied the human mobility data. The goal was to identify whether or not the control measures applied in China helped in mitigating the spread of COVID-19. A similar study which analyzed the human movements from technological sources was conducted by Tian *et al*. (2020). The study shows that cities which forced shutdown and banned traveling in China managed to control the spread of COVID-19.

To sum up, it can be noticed that many of the technologies that were adapted to control the COVID-19 pandemic are relying on solutions that use big data in developing applications based on Artificial Intelligence (AI) technologies. Thus, technologies that are influenced by artificial intelligence and big data analytics will be sufficient and effective in helping to manage the COVID-19 pandemic and others.

Materials and Methods

Artificial Intelligence (AI) Technologies for Mitigating COVID-19

Many countries have relied on various digital technologies during COVID-19 and in particular, have relied on artificial intelligence to develop applications that help them to contain and mitigate the COVID-19 pandemic. AI gained its importance before the outbreak of COVID-19. For instance, South Korea published its national strategy for artificial intelligence in December 2019 (Ministry of Science and ICT, 2019). In this strategy, South Korea outlined its prospects for AI, vision, goals, core strategies, tasks, governance and action plans. The main goal of this strategy is to set guidelines for South Korea to be a world leader in AI.

Public health is a core area in this strategy; thus, South Korea aims to be a global leader in using AI technologies in healthcare (Ministry of Science and ICT, 2019). With regard to the COVID-19 pandemic outbreak, South Korea is a leading country in using AI in its national strategy to mitigate this pandemic. This includes developing several AI tools such as Chatbot which is based on the IBM Watson Assistant tool to work as a care call service for people under monitoring (GRK, 2020).

Fig. 3: Categories of Artificial Intelligence (AI) tools for COVID-19

Technologies which have been developed using AI in response to COVID-19 can be classified into a number of categories in Fig. 3. These include AI technologies that help in diagnosing, surveillance, contact tracing, treatment, screening, monitoring and the management of medical clinics. This section will illustrate the most crucial methodologies and technologies which have been developed during the COVID-19 pandemic.

AI Prognosis Tools for COVID-19

There exist several works that have aimed to use AI techniques to identify the spread of COVID-19 among specific populations from an early stage. These works could provide early prediction in a good amount of time on which areas are infected more than others. An example of such a technique is used by Qin *et al*. (2020), who used a technique called "Social Media Search Indexes (SMSI)". This technique works by analyzing the common keywords searched by people to predict the number of possible infected people with COVID-19. They claim that, in some cases, this technique could identify confirmed cases of COVID-19 in a certain population within 10 days in advance (Qin *et al*., 2020). A similar work was conducted by Song *et al*. (2017) to investigate data obtained online on the fear of the spread of infection and the potential risk of being infected with the Middle East respiratory syndrome known as MERS (Song *et al*., 2017). For this purpose, a novel tool developed by Feng *et al*. (2021) that uses a Machine Learning (ML) model has been used to provide the early identification of COVID-19. This tool relies on clinical information rather than relying on CT images and can provide reliable results.

A further work that aims to identify the spread of crisis from an early stage is the work of Yang *et al*. (2020), in which the authors use a model called "Susceptible Exposed Infectious Removed (SEIR)" along with an artificial intelligence approach to predict the COVID-19 pandemic and its epidemic curve (Yang *et al*., 2020). To identify the importance of this technique, (Wynants *et al*., 2020) studied around 145 models that claim to provide prediction approaches for mitigating COVID-19 at an early stage. Some of these predictive models were diagnostic for detecting COVID-19 based on medical imaging. Other models that were surveyed were related to mortality risk, which would help in developing more reliable predictive models for the diagnosis and prognosis of COVID-19 (Wynants *et al*., 2020).

AI Diagnostic Technologies for COVID-19

There are several works which have been implemented using AI technologies for the purpose of diagnosing COVID-19. These technologies are mainly related to machine learning, deep learning and neural network methods. This section summarizes the most promising technologies developed in this regard.

For example, the work of Yan *et al*. (2020) developed a model based on machine learning for the diagnosis of patients infected with COVID-19. Similar works include the study conducted by Goodman-Meza *et al*. (2020) that developed an algorithm that increases the diagnostic capacity of COVID-19 inpatients. Further works that used machine learning algorithms for the prediction and diagnosis of patients with COVID-19 include (Hu *et al*., 2020; Zoabi *et al*., 2021; Brinati *et al*., 2020; Sharma, 2020; Rasheed *et al*., 2021; Usman *et al*., 2022).

One of the works in this part has been implemented by Metsky *et al*. (2020). This approach is based on CRISPR nucleic acid to detect COVID-19 using machine learning algorithms. There are other techniques which are used in the efforts of diagnosing COVID-19 that use AI technologies. Such techniques in this regard use blood tests through the adaption of machine learning algorithms such as in the work of Kukar *et al*. (2021); Soares *et al*. (2020); Brinati *et al*. (2020); Wu *et al*. (2020b).

Deep learning solutions are also common approaches in AI that have been developed during the COVID-19 pandemic. An example of such applications is the use of deep learning tools to provide a quick screening of COVID-19 patients with higher risks (Wang *et al*., 2020b). Works that also use such techniques for diagnosing patients infected with COVID-19 include the works of Fang *et al*. (2021); Albahli and Albattah (2020); Liang *et al*. (2020a-b); Minaee *et al*. (2020); Wang *et al*. (2021); Yoo *et al*. (2020); Wu *et al*. (2020c).

In this context, some works have been implemented for diagnosing COVID-19 using neural networks. An example of such a work is Saha *et al*. (2021), which developed a graph-based model using neural networks for detecting COVID-19 by examining chest CT scans and X-rays. Similar works in this regard have been implemented by Khan *et al*. (2020b); Ozturk *et al*. (2020); Apostolopoulos and Mpesiana (2020).

AI Technologies for Treating COVID-19

Discovering a treatment for a certain disease can prove to be challenging and may take years to achieve with a low success rate (Mohanty *et al*., 2020). There are a number of works that have proposed solutions for using AI in the effort to develop treatments for COVID-19. One of these early works is Jamshidi *et al*. (2020) which aims to define a platform that can assist in finding a treatment for COVID-19 with the use of artificial neural networks. In fact, neural networks can be of great help in the discovery of treatments for COVID-19 once they are used in the extraction process of visual features for COVID19 (Vaishya *et al*., 2020). In another work that studied how AI-related solutions can help in developing treatments for COVID-19, an AI tool called 'Benevolent AI' gave promising results for this purpose (Schultz *et al*., 2020).

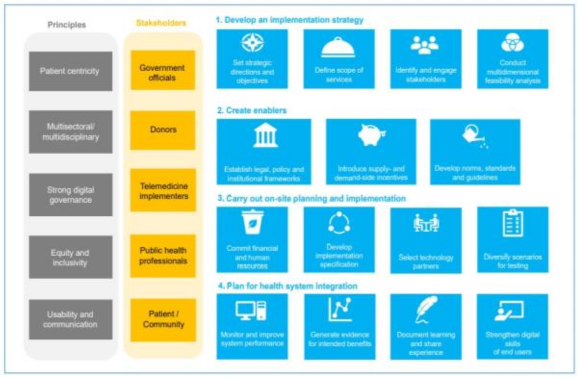

Fig. 4: WHO framework for telemedicine implementation WHO (2020)

One of the approaches that may use the help of AI tools to find a treatment for COVID-19 is drug repurposing. Drug repurposing is a technique in which an existing drug is studied to see whether it is suitable for use as a treatment of a disease that has been studied before (Mohanty *et al*., 2020; Cusinato *et al*., 2021). Works in this regard have used a network-based methodology with the assistance of AI for identifying a candidate reusable drug for targeting COVID-19 (Zhou *et al*., 2020a-b). Other studies have shown how using omics data with the help of AI technologies can propose a repurposed drug for treating COVID-19 (Ciliberto and Cardone, 2020; Barh *et al*., 2020).

Furthermore, AI technologies can have an important role in the process of developing a vaccine for COVID-19 as it can overcome many of the challenges associated with such a process (Arora *et al*., 2021). The work of Ong *et al*. (2020) used a machine learning-based tool called 'Vaxign-ML' in their efforts to identify the specifications that lead to developing an effective and safe vaccine for COVID-19. Another recent study concerned with identifying a vaccine for COVID-19 was conducted using two tools that are machine learning-based called 'OptiMax' and 'EvalMax' (Liu *et al*., 2020; 2021).

Therefore, it is clear how various AI technologies can be of great assistance in the development process of treatments for COVID-19. In fact, such technologies have been proven to be of huge help in the mitigating process of COVID-19.

AI and Telemedicine Technologies for COVID-19

WHO (2009) outlined the importance and urgency of telemedicine in controlling the COVID-19 pandemic (WHO, 2020). It has provided a detailed framework for the implementation of telemedicine in the fight against COVID-19, as shown in Fig. 4. This approach consisted of several principles including patient centricity, multispectral multidisciplinarity, strong digital governance, equity and inclusivity, usability and communication (WHO, 2020). It has also outlined the stakeholders associated with the implementation of this approach which consist of government officials, donors, telemedicine implementers, public health professionals and the patient/community (WHO, 2020). The approach has four main elements which comprise developing an implementation strategy, creating enablers, carrying out on-site planning and implementation and planning for health system integration (WHO, 2020).

Examples of Countries' Strategies for AI Telemedicine for COVID-19

The welsh health board launched a virtual tool that works on the IBM Watson Assistant AI tool called "CERi" (WHB, 2020). CERi is a virtual agent that aims to give answers and feedback about COVID-19 in two languages, English and Welsh (IBM News Room, 2020). The AI virtual agent was developed with the assistance of IBM natural language processing and Watson Discovery (IBM News Room, 2020). It can be accessed through computers, smartphones and tablets to provide many types of assistance with regard to COVID-19, including providing help to people dealing with emotional difficulties (IBM News Room, 2020). The tool has also been integrated with other tools to expand its capabilities. For example, CERi has been integrated with the symptom tracker tool developed by the welsh ambulance services (IBM News Room, 2020).

Australia is one of those countries that have implemented various strategies to successfully control the COVID-19 pandemic. One of these strategies is the implementation of telehealth services to provide virtual care for patients with COVID-19 symptoms (Hutchings *et al*., 2021). The strategy is set to virtually administer COVID-19 patients outside hospitals with several approaches including telephone facilities and videoconferencing (Hutchings *et al*., 2021). Furthermore, there are around ten telemedicine platforms providing healthcare to patients in France, which make them viable tools after the COVID-19 pandemic (Ahmed *et al*., 2020). The Government of Canada has also released a tool called the "COVID-19 App" (GC, 2020a) that aims to assess symptoms of individuals on a daily basis to determine whether or not these symptoms are related to COVID-19 and thus provide feedback regarding this.

Another significant work in this regard is the work of Ford *et al*. (2020) at the Medical University of South Carolina. It has used technology to develop a continuous system for delivering care during the COVID-19 pandemic. They have used biomedical informatics to develop four programs in order to provide COVID-19 patients with continuous screening and care (Ford *et al*., 2020). These programs aim to implement three strategies for mitigating and controlling COVID-19 through screening, testing and treatment. Their main tasks consist of: Providing urgent care through virtual screening, monitoring patients with COVID-19 remotely, reducing workforce risks and the utilization of personal protective equipment through continuous virtual monitoring and changing from outpatient care to telehealth care (Ford *et al*., 2020).

Similarly, the work of Jose *et al.* (2021) developed a strategy for managing the COVID-19 pandemic at Mayo Clinic. They designed a live registry in the EHR system based on a rule-based approach for classifying patients into five categories. One is for those patients who currently test positive for COVID-19, the second is for patients who recovered from COVID-19, the third is for those patients who suspect they have COVID-19, the fourth is for those who test negative for COVID-19 and the fifth is for those who are at risk of COVID-19 complications Jose *et al.* (2021). This system provided them with daily information about patients affected by COVID-19 and how to provide those patients with important supports regarding the isolation of contacts and care management Jose *et al.* (2021).

Examples of AI Telemedicine Tools for COVID-19

The importance of telemedicine in response to disasters was outlined far before the COVID-19 pandemic in several studies, for example in Lurie and Carr (2018); Uscher-Pines *et al.* (2018); Rolston and Meltzer (2015); Latifi and Tilley (2014) studies. With regard to COVID-19, the most common tool in this regard is IBM's virtual assistant AI tool (Watson) that is open to help in the response against COVID-19 (IBM, 2020). Tools which have been developed for this purpose can be classified into two categories: One is a self-assessment tool for symptoms of COVID-19 and the other is a contact tracing tool to identify close contacts of confirmed infected cases.

One common approach that has been deployed by many healthcare organizations throughout the COVID-19 pandemic is adapting telehealth tools such as voice assistants (Sezgin *et al*., 2020). The work of Sezgin *et al*. has studied the adoption of voice assistants in healthcare during the pandemic crisis and the readiness of the health systems and technology providers (Sezgin *et al*., 2020). Another technology in this regard is video teleconferencing which provides a two-way interactive tool for health consultation (Hollander and Carr, 2020). Such technology helps in minimizing the number of in-person visits to hospitals, reducing exposures between people and preserving medical resources (Hollander and Carr, 2020).

Not only telehealth services were implemented to provide care for patients infected with COVID-19; some telehealth technologies were also used to minimize in-person visits to medical facilities during this pandemic. Saudi Arabia is one of those countries which have developed alternative solutions that depend on telehealth technologies in order to provide healthcare for patients with diseases not related to COVID-19 during this pandemic (Yamin and Alyoubi, 2020). This was also applied in some of Turkey's hospitals by providing medical follow-up for children with chronic diseases through videoconferences (Aydemir *et al*., 2021).

DOI: 10.3844/jcssp.2024.465.486

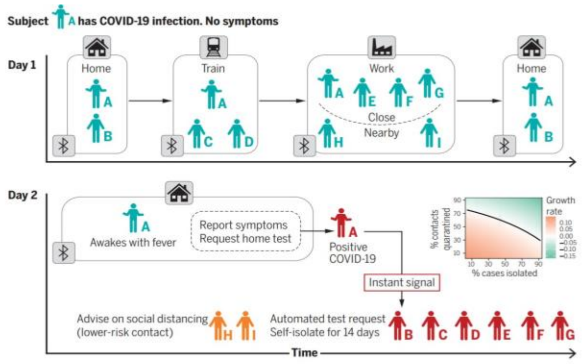

Fig. 5: Trace contacts of COVID-19 patients using Bluetooth low-energy technology Ferretti *et al*. (2020)

Crawford *et al*. (2021) study focused on studying how telemedicine can provide accurate surgical plans across orthopedic subspecialties. The results of this study have shown that around 4% of patients have their surgical plans changed after in-person visits. Such results show how telemedicine technologies are capable of providing support for the development of patients' surgical plans rather than in-person encounters.

Summary of the Advantages and Challenges of AI Telemedicine for COVID-19

It can be seen that telemedicine can provide several advantages in the context of a pandemic including ease of access, usability, the safety of health workers and patients and lower cost (Valentino *et al*., 2020). However, telemedicine may also raise some other concerns that are mainly related to data privacy and security (Callens, 2003). Major challenges for the adaptation of telemedicine during the COVID-19 pandemic are related to the readiness of the elderly population. A recent study conducted by Lam *et al.* (2020) showed that around 38% of the elderly in the US were unable to adapt to using telemedicine. This can be associated with a number of reasons including the lack of experience in the use of technology, having disabilities including hearing difficulties and communication difficulties (Lam *et al*., 2020).

AI Contact Tracing Applications for COVID-19

Since COVID-19 was declared a pandemic, many strategies and solutions have been developed in order to manage the most recent pandemic. Many of the efforts deployed in order to control the COVID-19 pandemic were related to the use of digital technologies. A very common approach, in Fig. 5, relies on digital applications to trace people's contacts in order to come up with a list of people who are at high risk when a person is infected with COVID-19 (Ferretti *et al*., 2020). This approach seems to be common in various forms, some of which depend on GPS networks to collect data or even relying on Bluetooth to gather the required data (Budd *et al*., 2020). Thus, many countries have adapted this approach by developing tools that work on smart mobile devices. This reviews some of these tools to show how they work to trace contacts of users who have been exposed to COVID-19.

Australia

Australia is one of the countries that contributed to developing a tool that aims to identify people who have been exposed to COVID-19-infected contacts. The tool is called COVID Safe and it works on Bluetooth signals to trace contacts of an individual who has either been diagnosed with COVID-19 or has been exposed to a person who is infected with COVID-19 (AGDHAC, 2023). It is stated in the official website of the Australian Department of Health that the tool does not track or save the locations of the users. Instead, it saves random keys which have been assigned to users for 21 days in order to trace the contacts of users exposed to COVID-19 within the last 14 days (AGDHAC, 2023). This means that the privacy of any user is kept safe from being exposed by third parties in an authorized manner.

Canada

The Government of Canada released an application called "COVID-19 Alert" with the goal of breaking the infection cycle (GC, 2020b). The COVID-19 Alert application uses Bluetooth to exchange codes between phones that are at close distances of less than two meters and for a duration of more than 15 min. It is claimed that the application neither uses GPS nor tracks locations; hence, it provides a higher level of privacy (GC, 2020b).

China

China has applied one of the strictest measures in mitigating COVID-19. In fact, it has enforced a strategy that consists of four elements; Isolation, contact tracing, quarantine of contacts and mass testing (Zhou *et al*., 2021). In terms of contact tracing, China has put in place a two major applications (Alipay and WeChat) that were responsible for the tracing contacts of infected people with COVID-19 (Liang, 2020). These applications were capable of identifying, assessing and managing people who has contacts with people infected with COVID-19.

Czech Republic

The eRouska application was developed by theˇ national agency for communication and information technologies in cooperation with the ministry of health in the Czech Republic (NACIT, 2020). The main purpose of this application is similar to the previous applications, which is to track the contacts of COVID-19-infected people. The application uses Bluetooth technology to transfer data between mobile phones and does not use GPS networks to track locations as stated in the official website of the application. The eRouska application canˇ be installed in both android and IOS mobile phones and it is claimed that it does not send identities to other users (NACIT, 2020).

Denmark

The health authorities in Denmark released an application called "Smittestop" which aims to identify those who have been in close contact with a person who has been diagnosed with COVID-19 in the last 8 days (DAPS, 2020). As stated in the official website of the application, it is voluntary to use and it uses Bluetooth to exchange data between different phones which have the applications downloaded on them. Data collected by different phones are sent to the Danish agency for patient safety for further processing and the agency ensures the privacy and security of this data (DAPS, 2020).

Finland

The Koronavilkku is an application developed in Finland by the (DHW, 2020). It uses Bluetooth to store codes of other phones which are at a close distance and keeps this data stored for 21 days. Its main goal is to control the spread of COVID-19 by tracing contacts of infected individuals or notifying users about infected people with whom they were in close contact in the last 21 days. The official website of the application claims that identities and locations are not stored, no personal data are collected and all communications are encrypted (DHW, 2020).

Germany

The application that is responsible for tracing infection chains of COVID-19 in Germany is called Corona-Warn-App (RKI, 2020). The application was developed based on a decentralized approach and it uses the exposure notification framework which uses Bluetooth to scan for the identifiers of other users which are in closed contacts of the primary phone (RKI, 2020). Data can be traced up to 14 days after contact with infected identifiers using an encrypted protocol to preserve the privacy and security of users (RKI, 2020).

Italy

Italy also uses an application that aims to notify users of a possible infection in case an exposure to an infected person is recorded. The application, which is called "Immuni", uses Bluetooth low-energy technology without the need for storing any personal data or any GPS data.

Japan

The COCOA-COVID-19 Contact app is a contact tracing application provided by the Japanese ministry of health, labour and welfare (JMH, 2020). It works in a similar way to the previous applications using Bluetooth technology on smart phones. The application was developed using API provided by Google and Apple and stores data for 14 days to notify users in case of an exposure to an infected person in that period (JMH, 2020).

Saudi Arabia

Tabaud is an application developed by the Saudi Data and Artificial Intelligence Authority (SDAIA) in Saudi Arabia in an effort of mitigating the coronavirus pandemic (SDAIA, 2020). It works similarly to the previous contact tracing applications, in that it identifies close contacts using Bluetooth low-energy technology. It also preserves the privacy of users by neither storing nor sharing personal information of the users and their locations (SDAIA, 2020).

United Kingdom

The United Kingdom National Health Services (NHS) has released the NHS COVID-19 application to help in managing the coronavirus pandemic within the UK (NHS, 2020). The application uses Bluetooth low-energy technology in smart phones to identify the distance and contact duration between all users of the applications, similar to the previous applications. It uses an algorithm called risk-scoring to alert users if they have been in close contact with a person who has been confirmed to have COVID-19 (NHS, 2020).

United States

Each state in the US has released its own version of an application that can be installed in smart phones to trace contacts of infected people with COVID-19. For example, Alabama has released the guide safe exposure notification application which was developed by the department of public health in Alabama with the cooperation of the University of Alabama (ADPH, 2020). The state of Arizona has also released its own application through the Arizona Department of Health Services which is called the COVID Watch Smartphone App (ADHS, 2020). The state of Virginia uses the COVID Wise application for this purposes which works in a similar approach to other applications used by the other states (VDH, 2020). All of these applications use Bluetooth low-energy technology to trace contacts of infected people in a similar approach to the applications developed in other countries.

Other Examples

There are also other countries which have developed similar applications to trace contacts who were exposed to COVID-19. An example of such a country is Austria, which released an application called STOPP CORONA Austrian Red (Cross, 2020). Belgium is developing an application called Coronalert (BGFE, 2020); Ireland released the Covid Tracker application (IHSE, 2020); the Netherlands released the CoronaMelder application (NMHWS, 2020); and Singapore released the Trace Together application (SGDS, 2020).

Summary

It is shown that AI contact tracing applications may provide several advantages to help in mitigating the COVID-19 pandemic. One is identifying infected people and tracing their contacts in the early stage before the virus is distributed to a wider range. The other advantage is the possibility of identifying regions which are more likely to be infected than others before the virus spreads to other regions. However, there are some concerns with this approach including ones that are related to the privacy of users including their personal information, their locations and the security of such data. Another drawback to this approach is that most of these applications do not provide real-time data since they totally depend on the contribution of users. Hence, this approach is a useful one but it cannot provide the only digital solution to the control of the COVID-19 pandemic. Moreover, it can be concluded that solutions which rely on one possible method to tackle the COVID-19 pandemic are not going to provide much help in this matter. Hence, there is a great urgency for combining all various approaches and technologies in one combined strategy to tackle the COVID-19 pandemic.

Challenges Associated with AI COVID-19 Related Technologies

Since there are many technologies and approaches that have been developed to control the COVID-19 pandemic, it is expected that there will be a number of challenges associated with these technologies and approaches. These challenges, in many cases, can be managed but in many cases it takes some time to do so. This section illustrates the most common challenges associated with many of the AI technologies developed for the purpose of mitigating the COVID-19 pandemic in Fig. 6. Recognizing such challenges helps to put management plans in place in the future from early stages. Some of these challenges are technology-based which means they are entirely the results of using or adapting certain technologies. The others are associated with the users of such technologies and these resulted from the types of users using these technologies.

Privacy can be described as one of the most important challenges facing all types of applications developed within the healthcare industry. Therefore, it is necessary to address this challenge as early as the starting stage of the development of any application. This can be achieved through many aspects to ensure that patients' sensitive data are used responsibly and are protected. In fact, it has been identified that the privacy of data is a major concern during the time of pandemics such as COVID-19 due to massive data sharing during this period (Fazal *et al*., 2022). The developed applications for mitigating COVID-19 such as contact tracing applications are among those applications over which there are concerns regarding data privacy (Mikkelsen *et al*., 2020; Zwitter and Gstrein, 2020). This can be avoided through classifying data based on a set of controls and regulations that are defined within the organization.

Fig. 6: Digital transformation challenges during COVID-19

Privacy

A recent study by Verri Lucca *et al*. (2020) has addressed a number of issues related to the privacy of patients' data during the period of COVID-19. The study suggests a solution to most of these issues by developing a solution that takes into consideration the privacy of data from four main aspects (i.e., taxonomy, cryptography, private profile and devices) Verri Lucca *et al*. (2020). This is not an easy task to achieve and in fact, privacy in many cases is considered the most important and difficult property to fulfil.

Security

Security is another important challenge facing all applications, especially if they are related to healthcare. Healthcare applications are some of the most important types of applications that need to address security from the early stages of development. They are associated with sensitive data that need to be protected extensively. In fact, if the integrity and availability of such data is breached, this would eventually cause massive damage to organizations in terms of cost and reputation. Most applications developed for the purpose of mitigating COVID-19 must have addressed this challenge since the chances of security breaches are most likely to occur to such critical systems (Zwitter and Gstrein, 2020). In a recent study, it was noted that around 90% of IoT devices use unencrypted transmission and 57% of such systems are vulnerable to cyber-security attacks (Aman *et al*., 2021).

It has been identified that applications developed for controlling COVID-19 must address defensive models from an early time of development against attack vulnerabilities (Rahman *et al*., 2020). In a recent report by Deloitte, the author provides a guiding technique that takes the security of data into consideration, stating that

DOI: 10.3844/jcssp.2024.465.486

data need to be considered when developing applications. This consists of several steps including reviewing and updating security strategies, performing security reviews, extending threat detection to remote devices, configuring secure VPNs, the encryption of all data and deploying multifactor authentications for security-critical applications (Batch *et al*., 2020). However, it is essential while deploying such security strategies and requirements not to affect the quality and performance of these systems (Hameed *et al*., 2021).

Interoperability

It has been identified that many healthcare systems lack interoperability including storing data in isolated databases, systems' incompatibility and difficulty in exchanging data (Lehne *et al*., 2019). In fact, this is a very common challenge for technologies which are developed in such a short period of time without having the chance to plan the integration of data within various systems in a more accurate manner. Interoperability can be classified into three categories consisting of technical interoperability, syntactic interoperability and semantic interoperability (Dash, 2020). With regard to COVID-19, the work of Liang *et al*. is one of the earliest to recognize this challenge and the authors propose an interoperable COVID-19 IoT platform using geospatial standards (Liang *et al*., 2020a-b).

The work of Tsiouris *et al*. (2020) recognized this challenge in telehealth applications, in which interoperable components are essential. The study proposes a platform that is capable of communicating and exchanging data between different components in an effective and efficient manner (Tsiouris *et al*., 2020). Many times, technologies need to talk to one another and thus, they must adapt to other technologies, especially when they require integrations from third parties. This seems to be a bit of a challenge for several technologies developed for the purpose of fighting COVID-19. Nevertheless, increasing data interoperability would eventually enhance the development of effective applications that aim to mitigate COVID-19 (Jeong *et al*., 2020).

Usability

This is another important system property that needs to be considered carefully in order to make programs more effective for customers. Usability is a major quality attribute and aims to improve the ease of use for users (Nielsen, 2012). It relates to how the system's layouts are designed and hence, creating more learnable, efficient, memorable, error-free systems for all types of users (Nielsen, 2012). Usability is considered to be one of the most important requirements when it comes to health-related applications (Mathews *et al*., 2019). Health experts are highly recommended to have health-related applications such as telemonitoring technologies to measure their usability before launching them to patients in order to gain the best outcomes from them (Cruz *et al*., 2014).

In many cases, the design of systems is left until a later stage of development which results in more difficulties in using them. This seems to be the case in some of the applications developed during COVID-19, of which many have been proven to be effective but there are issues related to usability (Golinelli *et al*., 2020a). Therefore, there is a huge need for considering the usability of these applications and allowing their intended users to test them before they are launched (Lim *et al*., 2021). A recent study that focused on studying the usability among users of a self-triage website for COVID-19 illustrates the importance of usability for such applications and how it results in more effective outcomes (Schrager *et al*., 2020).

Reliability

Another common challenge that faces the new technologies developed to mitigate the COVID-19 pandemic is to deliver reliable systems (Javaid and Khan, 2021). Reliability has always been a concern and during this pandemic, people are looking for solutions that they can trust with results they can rely on. In terms of AI applications, the challenge of developing a reliable solution that is based on AI architecture has always been rising (Khan *et al*., 2020a). In fact, many of the systems developed for mitigating COVID-19 in specific tasks still lack in providing reliable information for patients (Nguyen *et al*., 2020).

Data sources' heterogeneity can be seen as the main reason for causing many of the AI systems for mitigating COVID-19 to give unreliable results (Ndiaye *et al*., 2020). For example, IoT technologies that were developed for contact tracing and monitoring social distancing face a reliability concern (Ndiaye *et al*., 2020). A recent work by Rashid and Wang recognized this concern by developing "CovidSens". It is a system that aims to provide the public with reliable alerts and monitoring of the spread of COVID-19 (Rashid and Wang, 2021). However, reliability is still a major concern in this regard and systems need to address it carefully.

Acceptability

In many cases of digital transformation, a common challenge is how users will accept the new change (Ricciardi *et al*., 2019). Users' resistance to new technologies is common and it usually takes some time for users to adapt to a new technology. In a previous study conducted by Nadarzynski *et al*. (2020), it showed that 70% of surveyed patients preferred physical consultations and only 3% preferred video consultations. Furthermore, the study has shown that only 17% of patients preferred telephone consultations while only 10% preferred webchat consultations (Nadarzynski *et al*., 2020). Therefore, it was not surprising that many of the technologies developed during the COVID-19 pandemic have some resistance and it took time for users to start using them. If users of these systems feel there are violations of trust and ethical values, then this would result in losing their trust and hence, there would be a lower likelihood of acceptability for these systems (Mbunge *et al*., 2021).

There was a study conducted in Australia which measured the acceptability of the COVID safe application (a tracking application for COVID-19). The study had concluded that 62-70% of people who participated in that study have accepted such an application but there are still concerns related to the security and privacy of their personal information (Garrett *et al*., 2021b). A similar study conducted in Taiwan has identified the acceptance of tracking technologies for COVID-19 is around 75% among young adults aged 25 and younger (Garrett *et al*., 2021a). However, the case is not the same in France, in which only 19% of participating people are supportive of tracking applications for COVID-19 (Touzani *et al*., 2021).

Results and Discussion

Proposed Strategic Model in Healthcare for AI-Related Technologies

Existing health risk management models do not consider adapting digital technologies from early stages. In fact, technology has always been a risk factor to consider when putting in place a health risk management plan due to cyber-attacks and data privacy risks (RSA Security, 2020). Therefore, many of these models need to be redesigned to allow digital technologies to work as supporting factors in any risk management plan. This will eventually help in mitigating health epidemics and pandemics from early stages.

This section proposes a strategic model that aims to consider all the previous technologies developed for mitigating the COVID-19 pandemic and challenges associated with these technologies. This strategic model is described below in more detail including its elements and how it is deployed.

Model Stages and Elements

It has been shown that new technologies that make use of AI can provide huge help with mitigating and controlling the COVID-19 pandemic. All technologies developed during this pandemic have used one or more of the technologies in Fig. 7. The strategy which can be summarized from these digital solutions which were adapted and developed to mitigate the COVID-19 pandemic are divided into two main categories. The first can be called "proactive" and it is related to all the approaches, solutions and technologies and the main objective of it is to prevent the pandemic from reaching certain regions and spreading. The other category can be called "reactive" and it relates to all possible strategies and solutions which are used to control and contain the pandemic from further distribution and even ending that pandemic.

However, there is a great need to modify such a strategy in order to achieve better results in controlling any pandemic with the support of digital technologies. The modifications for such strategies must include an early step responsible for predicting such pandemics from occurring and the set of actions required. Figure 8 shows a model that takes into consideration such concerns. The model is divided into three stages in which each stage will have a number of required actions in order to control a health crisis such as the COVID-19 pandemic. Healthcare digital applications need to be associated with each stage of the model in order to make the best use of them during a certain crisis. These stages are defined after surveying many of the existing risk management models in literature and they summarize the most relevant approaches considered in these models.

Fig. 7: COVID-19 digital technologies

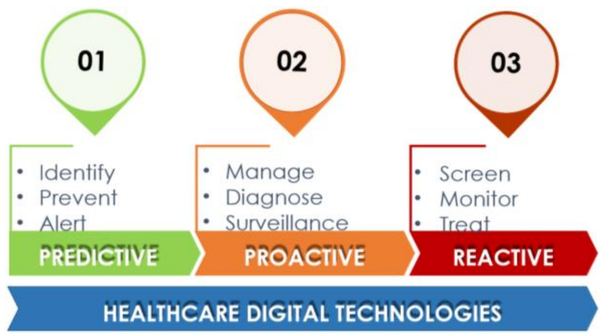

Fig. 8: AI-related strategic model for healthcare digital technologies

Fig. 9: AI-related strategic model deployment steps

Predictive

The predictive stage represents the first stage in regard to developing a model that can mitigate health pandemics from early stages. In fact, this can be seen as the most important stage and the first defence line for any risk. It is the one responsible for predicting a pandemic before its occurrence and hence avoiding it. This stage is the one responsible for developing digital applications that can give an early prediction of a specific pandemic that might occur. This stage consists of three elements, each of which has a specific job in the prediction stage. Furthermore, each of these elements will be associated with certain applications that can achieve the objective of the prediction stage. These include the identification, prevention and alerting elements.

Proactive

The second stage is the proactive one which is as important as the first one and can be seen as the second defence line. This stage can be seen as the one which accepts the occurrence of a particular pandemic or risk and hence it provides actions to achieve this purpose. Therefore, it is the one responsible for managing, diagnosing and surveilling a risk which is most likely to occur. Therefore, specific digital technologies need to be developed to achieve one of these objectives.

Reactive

The third stage is the reactive one and it is as important as the previous ones. It is the one responsible for controlling pandemics after their occurrence. Actions required at this stage are related to making a certain pandemic less severe and ending it. They consist of screening, monitoring and treating a risk that has already occurred. Hence, any application developed during this stage must be carried out to achieve one of these requirements.

Model Deployment

In order to implement the strategy described above in a successful manner, it is necessary to follow a certain number of steps. These steps ensure that every AI tool that is developed can serve the purpose it is developed for. These steps need to be followed for every product developed to achieve the task of a certain element in this strategic model. These steps can be described as a guide for new developments of any AI-related tools and hence they can address all challenges associated with such developments. These are comprised of four steps as illustrated in Fig. 9 and they are described below.

Plan

This is the first step which should be taken before starting any development of a project. It aims to conduct a very comprehensive planning for a project ahead of starting it. The planning step should have a number of outcomes including purpose, scope, timeframe, deliverables and team organizing. Once this step is carefully conducted, then it will overcome most of the challenges described previously such as security, privacy and reliability. More specifically, the planning step can be described as the one which must consider all previously described challenges.

Develop

This step is related to the development phase of a project and it has a number of outcomes which need to be accomplished before moving to the next step. Outcomes related to this step consist of choosing the best methodology for developing and designing a prototype. It is also necessary to consider testing and putting in place testing cases before the final launch of the product. Once this step is considered thoroughly, then most of the crucial challenges associated with AI-related tools can be avoided, i.e., mainly privacy, security, interoperability and usability.

Execute

This step represents the one which shows how the final product is delivered and considers all the outcomes of the previous two steps. It also consists of other tasks including the monitoring and control of the project. It also needs to consider raising awareness of the new products in order to increase the acceptability among users. This stage also needs to be conducted professionally in order to avoid challenges associated with it, particularly reliability and acceptability.

Measure

This can be described as the last step of the project and it is a continuous process. In fact, it is essential for any application developed to be effective in healthcare risk plans to have Key Performance Indicators (KPIs). KPIs for such a purpose are essential to assess and give valuable feedback about the effectiveness of new technologies put in place for similar purposes. Once this stage is conducted, then it would provide an approach for measuring the effectiveness of the AI-related technologies developed at this stage. This means that the reliability and acceptability challenges of such tools are considered, which would eventually lead to improvements of such tools.

A Proposed Predictive IoT Architecture

In order to show how the proposed strategic model could be implemented in real cases, below a described architecture for a predictive healthcare intelligent system. This architecture describes how to develop a predictive system for the predictive stage in the strategic model with specific roles in identifying, preventing and alerting the outbreaks of pandemics. The proposed architecture which is shown in Fig. 10 is based on the Human-in-the-Loop predictive model proposed by Ganesan *et al*. (2021). It involves the inputs of humans and artificial intelligence algorithms in order to produce accurate results.

This architecture is mapped to the three-layer IoT architecture with designated responsibilities for every layer. For instance, the IoT perception layer in this predictive system is responsible for collecting data from the environments which they are operating, then such data is transmitted using the network layer. In fact, using advanced network technologies such as 6G in this layer would allow data to be transmitted and processed faster and hence leading to more accurate predictions (Hou *et al*., 2022). The application layer which is the most important one processes the data using intelligent algorithms with the help of inputs from humans and historical data in order to give more reliable processing for the collected data. Once a decision is reached, it is stored in this layer and transmitted to the perception layer so it can be announced.

A certain scenario which could be implemented using this proposed architecture is to collect data from IoTs distributed in organisations other than healthcare ones. For example, data collected from face recognition cameras in airports for people with signs of a specific disease appearing in their faces could give alarming signs of an epidemic outbreak before it occurs. The proposed architecture in Fig. 10 would be very applicable in collecting such images and analysing them using AI processing algorithms, historical data of diseases and interactions of specialised personnel. This would eventually lead to predict whether or not such people have certain diseases.

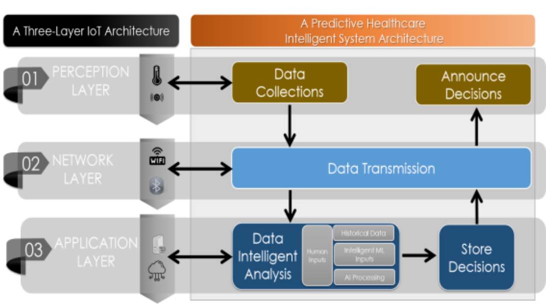

Fig. 10: Proposed predictive healthcare intelligent system for IoT architectures

Conclusion

It has been identified that Artificial Intelligence (AI) technologies have a major impact on mitigating COVID19. This study surveys the existing technologies that have been adapted using artificial intelligence to mitigate the COVID-19 pandemic. Many works aim to develop AI-related tools for either controlling, diagnosing, or treating COVID-19. This study has outlined these tools and how they are used to mitigate COVID-19.

One of the technological advancement during the pandemic of COVID-19 is the use of advanced telemedicine tools for many health purposes. Telemedicine can provide healthcare organizations with the potential to reduce the number of in-person visits, to minimize exposures and to preserve medical resources. This study has outlined how telemedicine technologies were developed and used with issues associated directly with COVID-19 such as diagnosing patients with COVID-19 symptoms. Other telemedicine tools are directed at patients with medical issues that are not related to COVID-19. Many countries have also adapted other advanced AI tools. An example of such is contact tracing applications which were developed to identify people who have been in contact with patients infected with COVID-19.

AI technologies that aim to control COVID-19 in various countries have faced several challenges. This study has outlined the most common of these challenges and how identifying these challenges from the early stages can help in avoiding them. It has been identified that the most common challenges associated with such tools are related to privacy, security, interoperability, usability, reliability and accessibility. The paper concludes by proposing an AI-related model that can be used as a guiding plan for mitigating pandemics throughout all stages using advanced technologies such as AI and big data analytics. This model can help in controlling, managing and avoiding pandemics similar to COVID-19. It can be concluded that AI-assisted technologies have played a vital role in mitigating and controlling the COVID-19 pandemic.

Future directions to this study can be expressed in several areas. However, it can be said that the most challenging extension to this study is to apply it on simulated cases in which could happen in a simulated lab to check the results of the model. This would definitely allow more data to be collected and hence provide more validation for the defined model. Another future extension is to integrate the model with other models designed for developing AI technologies such as IoMTs. Once it is integrated then it can be tested using existing health crisis scenarios in order to prove its applicability with various technologies.

Acknowledgment

I would like to thank the anonymous reviewers for their valuable and helpful comments.

Funding Information

The author confirms that there is no financial support or any funding received to this research.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues involved.

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