IoT-to-the-Rescue: A Survey of IoT Solutions for COVID-19-like Pandemics

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***Abstract*—The atmospheric buoyancy and intangible nature of fatal communicable viruses lead to rapid transmissions among individuals, resulting in global pandemics. Strategic lockdowns and mandatory social distancing are immediate solutions in such scenarios. However, this leads to operational disruptions in education, manufacturing, economy, transportation, governance, and community. Although technological assistance is beneficial in overcoming such issues, the current Internet of Things (IoT) infrastructure has limitations. In this paper, we provide a comprehensive review of the possible IoT-based solutions that have the capacity of combating the COVID-19-like viruses. We highlight the societal impacts due to pandemics and identify the specific lacunae in current IoT solutions. We also provide comprehensive detail on how to overcome the challenges along with directions towards the possible technological trends for future research. Compared to existing reviews, our work offers a holistic view of the cause, effects, and the possible solutions that are existing, along with already existing solutions that can be customized to serve the special needs during the pandemic.**

***Index Terms*—COVID-19, Internet of Things, SARS-COV-2, Pandemic, healthcare, Education, Transportation, Industry, Governance, IoT architecture, .**

I. Introduction

Pandemics have the potential to cause global disruptions and chaos in society. The recent COVID-19 pandemic has shown how, even in this modern age with cutting-edge healthcare and technology, pandemics are still an imminent threat. COVID-19 has spread rapidly across the globe, leading to umpteen fatalities. The virus spreads from one person to the other through droplets spread during coughing and sneezing. These infected droplets enter a healthy person through the nasal and mouth openings, binding the virus to the cellular receptors before multiplying. Restricting the spread of the COVID-19 disease is challenging due to its intangible nature, which eventually led the World Health Organization (WHO) to declare it as a Public Health Emergency of International Concern [1]. Under such circumstances, adoption of technological advancements such as the Internet of Things (IoT) coupled with artificial intelligence/machine learning techniques and upcoming 5G/6G technologies is beneficial for combating the pandemic [2]. IoT solutions have the potential to provide a fully/semi-automated system for identification, tracing, tracking runaway patients, alerting concerned authorities, and others to decrease the response time of the authority. For instance, a thermal scanner may identify an infected individual and use cameras to store facial images into a secured database (centralized/decentralized). The IoT system may alert the concerned authorities for taking necessary measures and isolating the person. A similar system may be used for surveillance at the containment zones. Some of the other areas where IoT solutions find scope in combating the pandemic are, but not limited to, shopping malls, construction sites, factories, public spaces, market places, hospitals, educational institutes, and others. However, no *one solution* that fixes all problems exists, which leads the authorities to make fallacious decisions. Smart selection from the possible solution techniques and their deployment is necessary for overcoming the aforementioned issues. Owing to the current pandemic, there have been various surveys to study the effect of the pandemic on different domains [3] [4] [5]. The majority of these surveys focus on the role of IoT in managing the pandemic in a specific domain, especially in healthcare. Surveys such as [6] and [7] focus on the use of IoT solutions for the ehealth sector, and surveillance and monitoring in healthcare setup.

In this work, we present a comprehensive study of the possible IoT solutions for combating the COVID-19 pandemic and restricting its spread. We identify the major application domains affected by the pandemic and its impact on society. We highlight the major concerns in each of these domains and discuss how the government, together with healthcare and pharmaceutical companies, may help in returning the order. While the healthcare and pharmaceutical industry work towards developing vaccines, regular diagnosis pertaining to long, short, and intermediate treatment is currently disrupted. Most government healthcare centres actively test for identifying infected individuals, which increases the cost of regular care and medication. Economies are affected due to restrictions on travel and tourism, which involve flights, trains, cars, and other transportation facilities. Industrial operations involving manufacturing and supply chain are also affected due to restrictions on transportation sectors, increasing the cost of raw materials, which further worsens the economy. We also identify and discuss how the pandemic has led to predicaments in the current IoT infrastructure and highlight how the available solutions in literature fall short in providing a solution to the pandemic. We account for the limitations in the conventional IoT and suggest methods to overcome the same. We present this work with the motive to provide a guideline of possible techniques for tailoring the current IoT infrastructure towards achieving "*IoT to the Rescue*" under

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pandemic-like situations.

In light of the existing works, we try to evaluate the overall societal repercussions of COVID-19 and how IoT can be used to improve the situation. While healthcare-related issues are undoubtedly the primary concerns in the times of a pandemic - to help contain and control the disease and post-infection procedures to mitigate its effects, there are other domains, such as transport, manufacturing industries, logistics and others, that are severely affected by the pandemic and the application of IoT can bring a sense of normalcy and control in these domains. We culminate these observations together in our work and focus on the role of IoT in different domains, rather than just focusing on the technology-wise IoT-based solutions for the COVID-19 pandemic. Our multi-dimensional study will help the readers get a holistic view of the COVID-19-affected areas and how IoT is being used and can be used to ameliorate the condition. Table I presents a comparative analysis of some of the existing survey articles on the role of IoT in the COVID-19 pandemic.

We followed a systematic design for executing the survey. The research papers were selected in multiple phases and filtered based on the application domain, solution method, novelty of the work, and age of information included in the research papers. In addition to the research papers published in reputed journals, articles from online sources were also referred to.

TABLE I: A comparative analysis of the existing survey research article on role of IoT during COVID-19 pandemic.

Work	Governance	Industry	Healthcare	Transport	Tourism	Education	Social Engagements
Ndiaye *et al.* [8]	X	X	X	✓	X	X	X
Dong *et al.* [9]	X	X	X	✓	X	X	X
Chamola *et al.* [3]	X	✓	✓	X	X	X	✓
Wang *et al.* [10]	✓	X	✓	X	X	✓	✓
Kumar *et al.* [11]	X	X	✓	X	X	X	✓
Nasajpour *et al.* [5]	X	✓	✓	X	X	X	✓
Kumar *et al.* [12]	X	X	✓	X	X	X	✓
Shen *et al.* [13] (robotics only)	X	✓	✓	✓	X	X	✓
IoT-to-the-Rescue (this article)	✓	✓	✓	✓	✓	✓	✓

A. SARS-COV-2: The Chronology of Events

COVID-19, an acronym for Coronavirus Disease - 2019, is an infectious disease caused by a novel virus from the Coronavirus family- SARS-CoV-2. Other diseases caused by the same family of viruses are the MERS and SARS. The situation is worsened by the fact that the virus, which causes COVID-19, has been identified for the first time and currently, there is no specific treatment or medication to treat the infection. According to the reports by the WHO, the first report of pneumonia with an unknown cause was reported by China on December 31, 2019. On January 30, 2020, the disease was

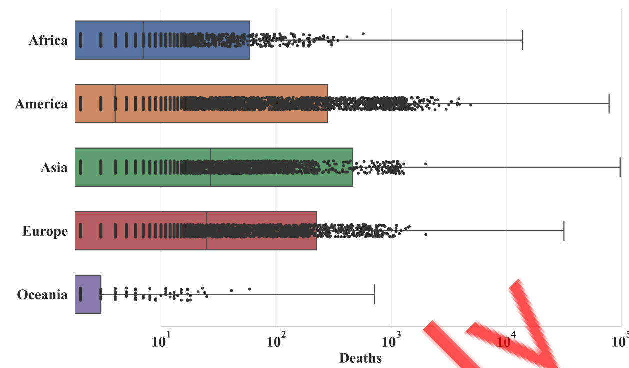

Fig. 1: A continent-wise outline of the spread and death of COVID-19 till October 2020.

declared a Public Health Emergency of International Concern by the WHO [1]. Since then, it has spread to 213 countries as of June 2020, with a total of $6,607,825$ positive cases. Fig. 1 outlines the spread and impact of COVID-19 across continents. Continents such as Asia, America, and Europe have been the worst affected in terms of the number of fatalities caused due to COVID-19 positive cases. The frequent interchange of the human population among these continents has been the major contributor to this uncontrollable spread. Fig. 2 shows the pairwise comparison of the number of detected cases worldwide and the associated deaths from these cases. A significant number of deaths were reported globally by the fourth month of 2020 (April) owing to the lack of protocols and norms for societal interactions and mechanisms for controlling the spread. However, even after considerable measures have been put in place (such as social distancing, quarantine, travel restrictions, and others), the number of positive COVID-19 cases has kept on increasing, even as recent as the tenth month into the pandemic (October 2020). A similar trend is observed in Fig. 3, which presents a monthly chronology of the spread and the percentile deaths associated with the pandemic.

B. Mechanism of SARS-COV-2 Infection

The major hindrance in controlling the spread of COVID-19 is attributed to the way it is transmitted. According to popular scientific theories and evidence-based studies, COVID-19 infection spreads by the droplets of saliva or bodily fluids transmitted in the air or an object by an infected person during coughing, sneezing, or even talking [14]. The virus attaches itself to the ACE2 receptors in the human body, primarily the lungs and respiratory tracts, and attacks the healthy cells. The infection begins with symptoms of common cold, which may lead to severe pneumonia and other respiratory diseases [15]. The virus can sustain and infect inanimate objects and their surfaces for 2 hours to 5 days depending on the type of material, such as wood, plastic, steel, copper, and others [16]. These infected objects that act as a medium of virus transmission between hosts are termed as *fomites* [17]. Any healthy person who comes in contact with any fomite gets infected. Fig. 4 shows the cumulative statistics for infections per 14 days per

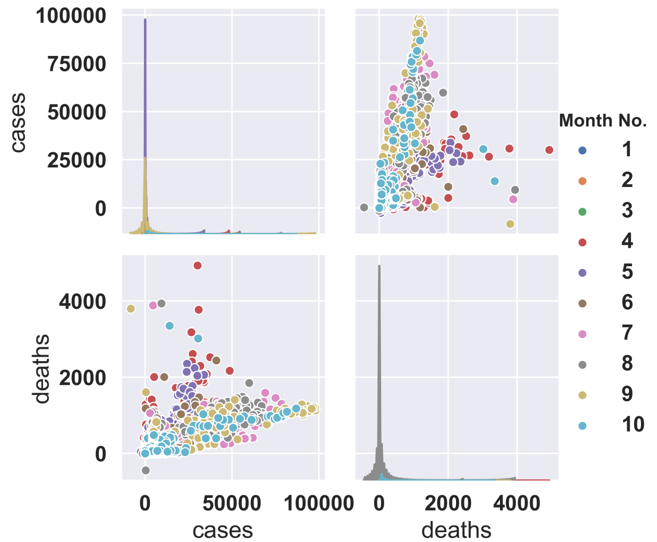

Fig. 2: A pairwise comparison of monthly case/deaths globally till Oct. 2020.

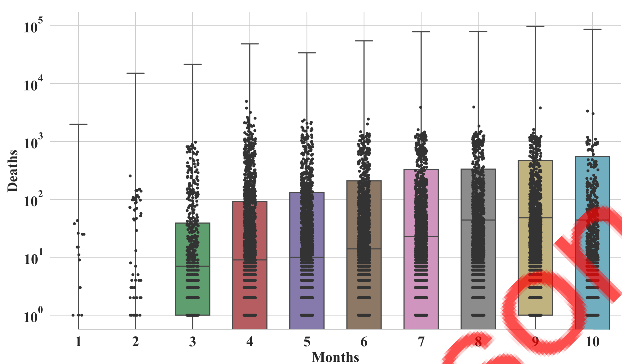

Fig. 3: A month-wise outline of the global spread and death caused by COVID-19 between Jan. – Oct. 2020.

100,000 of the global population. The observation window is between January (month-1) to October (month -10) 2020. It is observed that although there has been a sudden surge in cases between months 4 and 5, the growth rate has become more or less constant. This stabilization has resulted mainly from the various government policies to check the spread of this infection and the paradigm realignment of how society behaves and interacts in times of pandemics.

Currently, there are some vaccines for COVID-19 and are being rolled out. However, we still need to wait to know its efficiency in effect. There are ongoing researches by numerous organization, both private and government, worldwide. According to the advisory issued by the WHO, the spread of this infection can be stopped by restricting physical contacts between infected and healthy people, avoiding crowds, public gatherings, and regularly cleaning hands with soap and alcohol-based hand sanitisers. If a person is suspected to be infected or have early symptoms, she/he is advised to be quarantined and isolated until the status of infection is

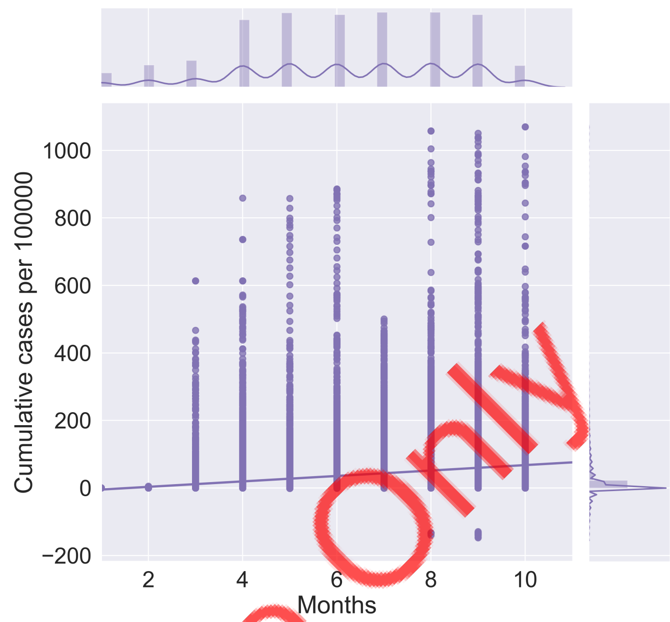

Fig. 4: A month-wise distribution of the cumulative cases for 14 days per 100,000 global population from Jan. – Oct. 2020.

confirmed. COVID-19 has raised concerns and challenges in different domains of the present world, starting from normal household activities such as grocery shopping to international trade and relations.

C. Motivation

IoT has multiple applications to offer towards managing the current global pandemic outbreak. While the primary focus of the research community is on enabling diagnosis and prediction of the disease itself, the effects of the pandemic on the socio-economic front cannot be neglected. Moreover, it is crucial to identify the limitations of the current IoT infrastructure. The readers should be aware of all the dimensions being affected due to the COVID-19 virus and how a tailored IoT has the potential to bring relief to pandemic-like situations. A thorough discussion is needed on the interlinked challenges and existing solutions to identify the possible solutions that can be modified to cater to other affected domains. These reasons act as the motivation for our study and presenting a guideline towards fighting the pandemic with technological solutions such as IoT.

D. Contributions

In this work, we bring together the effect of COVID-19 and solutions that are being pursued by the research community and industries towards controlling the effects of the pandemic in various fields using IoT. We discuss the challenges and limitations of the current state of the art solutions and provide methods for overcoming the same. The major highlights of this work are:

- ***Ramifications:*** We identify the effects of the COVID-19 virus on various application domains and highlight its impact on society. In this work, we try to identify all

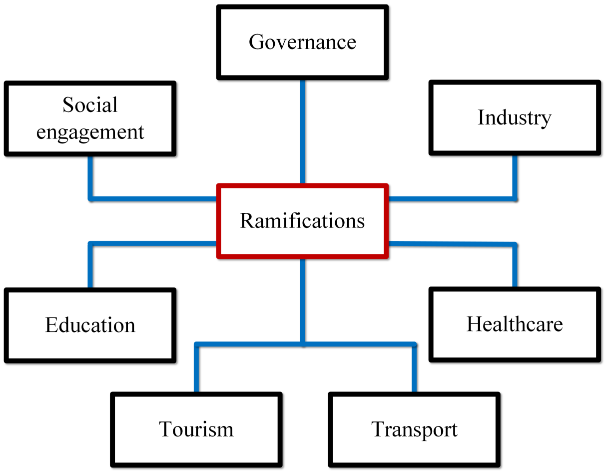

Fig. 5: Affected components of the societal fabric.

the major domains that have been faced with challenges arising due to COVID-19, which is not restricted to only the healthcare domain.

- ***Challenges experienced by conventional IoT solutions and technologies:*** We present how the current IoT-based and IoT-enabling techniques fall short in mitigating the effects of the pandemic-like situation. We extend our survey beyond the healthcare domain and bring together other domains and applications that are powered by IoT and are facing challenges due to erratic behaviour.
- ***IoT to the Rescue:*** We present methods and applications for overcoming the challenges encountered by the current IoT solutions in literature and combat the COVID-19 virus effectively. The solutions consist of both novel and new proposals and applications as well as existing methods that can be useful in the current scenario in the wake of the pandemic.

It may be noted that although systematic, the relaxation of the lockdowns across the globe will eventually lead to the further spread of the virus. In such scenarios, guidelines for possible IoT solutions such as this work are of paramount importance.

As shown in Fig. 6, we organize the rest of the paper as follows. We present the ramifications of the COVID-19 virus and its impact on society in Section II. We then present the lacuna in the current IoT infrastructure in Section IV and then present solutions towards overcoming it to achieve IoT to the Rescue in pandemic-like situations in Section V. We discuss further limitations in Section VI-B. We then present the future scope of IoT and its applications in Section VI-C and finally conclude in Section VII.

II. Ramifications of COVID-19

SARS-COV-2, a virus that has infected billions of humans around the globe, is distressing social and economic arrangements. According to a report by the United Nations (UN), COVID-19 is the worst health crisis in the last 75 years [18]. It has not only affected the health of the global population but created a complete pandemonium worldwide [19]. Healthcare infrastructures have collapsed, social activities have come to a complete stop, governments are being held responsible for taking harsh decisions to control and contain the spread, eventually leading to a crumbling economy. Fig. 5 highlights some of the major domains which have been severely affected by the COVID-19 virus. However, as shown in Fig. 7, we first highlight how the government, healthcare, and pharmaceutical sectors may help society in returning the order.

A. Resuscitate the Society

The government has a significant role to play in spreading the knowledge on the COVID-19-like viruses among the mass and its ramifications. On the other hand, the healthcare sector needs to keep regular treatments active in addition to those infected with novel viruses. Although these sectors have a significant role to play, they also suffer from challenges during such times, and we highlight them in the subsequent sections.

1) Government: The government is responsible for setting policies, regulating services, and reviving the economy in addition to returning societal normalcy. Fig. 8 depicts some of the primary components and sectors associated with the aforementioned responsibilities of the government during pandemic-like situations. Many countries have implemented policies, such as nation-wide lockdown to prevent the spread of COVID-19. Digitizing government services to enable remote services and supporting the hard-hit economic sectors for reviving the economy is a major challenge for the governments.

2) Healthcare Services: One of the most important and emergency sectors during the COVID-19 outbreak, the healthcare industry, is being pushed to work at its maximum efficiency to combat the pandemic situation. We categorize the healthcare treatments according to their stretch (immediate, short-term, long-term, and emergencies) in Fig. 9 and represent some of the primary components of the healthcare sector responsible for assisting the patients during pandemic-like situations. Restricted mobility and lockdown have affected patients suffering from other diseases who need immediate medical attention.

3) Pharmaceuticals: Pharmaceutical industries are under tremendous pressure to develop vaccines and drugs for the prevention and treatment of COVID-19. Supply chain and logistics have affected the import and export of raw materials and drugs. The cost of raw materials has increased, which will eventually result in increased costs of medicines [20]. As per a report of 2019, Asia was the second-largest exporter of drugs and medicines with an approximate share of about 9.5% of the global share. The availability and cost of drugs are major concerns as China and India are the prominent suppliers of drugs and raw materials for pharmaceutical companies, and both countries are facing major economic and social distress due to COVID-19.

B. IT and Programming

The IT and programming sector has witnessed declining business and increasing layoffs of employees. It is estimated that COVID-19 may have a more serious and harsher effect on the IT industry compared to the recession of 2009. The hardware infrastructures, such as data centres, and servers require human presence and intervention for their operation,

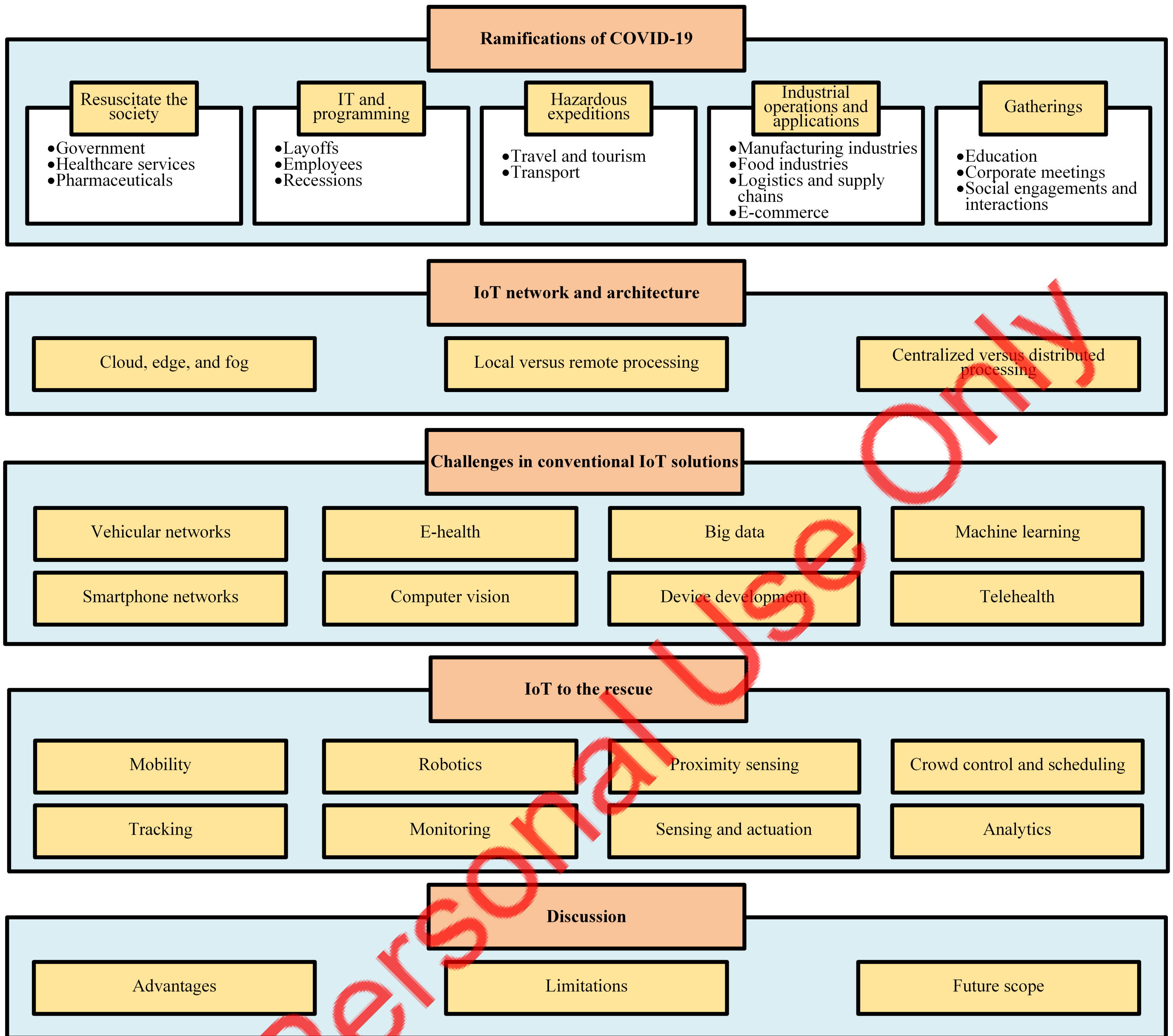

Fig. 6: Organization of the manuscript.

control, and management. On the other hand, tasks related to software such as programming and online job processing can be easily adapted to be accessed remotely.

C. Hazardous Expeditions

Movement from one location to the other during pandemic-like situations, especially when dealing with infectious viruses, is hazardous. Maintaining social distancing norms while travelling by public transport such as buses, flights, cabs, trains, and ships are challenging, which increases the chance of contracting the virus.

1) Travel and Tourism: According to a report by the World Tourism Organization (UNWTO), the first quarter of 2020 has seen a fall of approximately 22% in the international tourists' arrival. In view of the present scenario, it is estimated that the year 2020 may suffer a decline of 60% to 80% in international tourists' arrival compared to 2019. This is the worst setback that world tourism has seen since 1950 as per the reports by UNWTO [21]. About 120 million jobs are estimated to be affected, which are directly connected to tourism.

2) Transport: Different nations worldwide implemented lockdown with restricted to no mobility and transport services to contain the spread of the virus. Since the virus can survive on the surface of inanimate objects from hours to days, public transports are considered a major carrier of the virus. Local transports were restricted to emergency services and essential supplies. Many jobs and livelihoods depending on this sector have been deeply affected [22].

D. Industrial Operations and Applications

Industries cover a plethora of domains and services, as shown in Fig. 10. In the subsequent sections, we highlight some of the

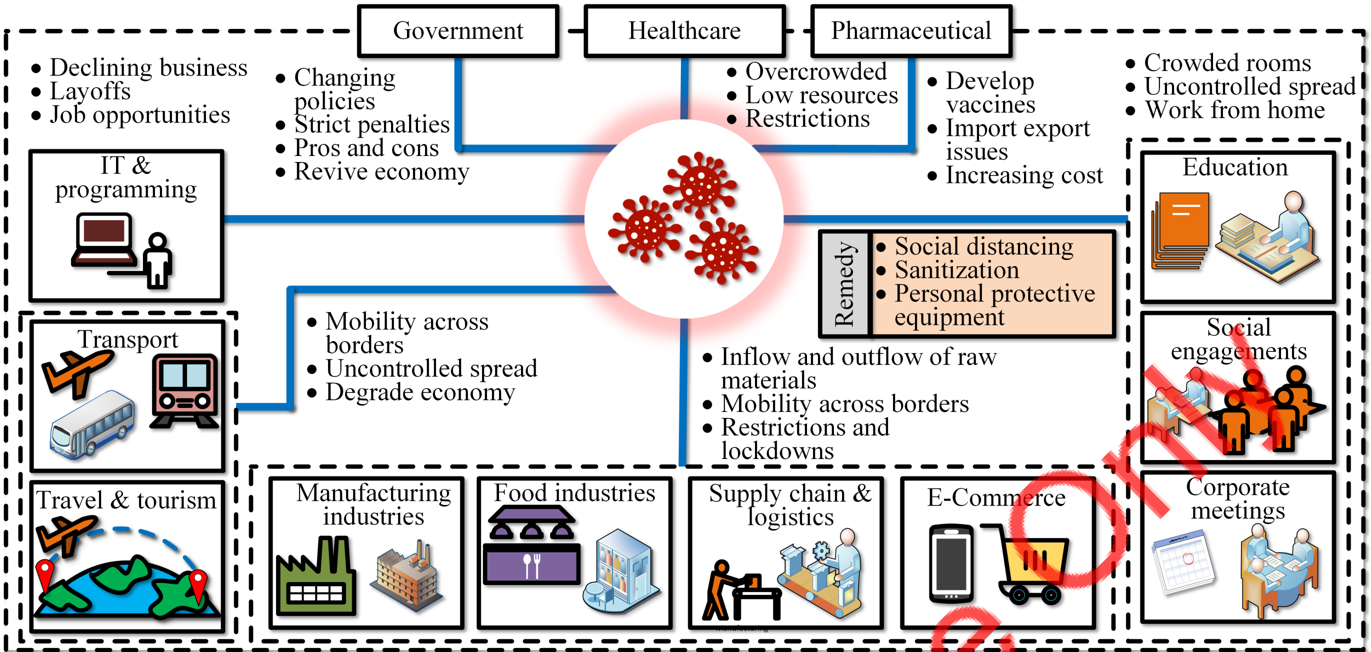

Fig. 7: Ramifications of the COVID-19 virus on major application domains.

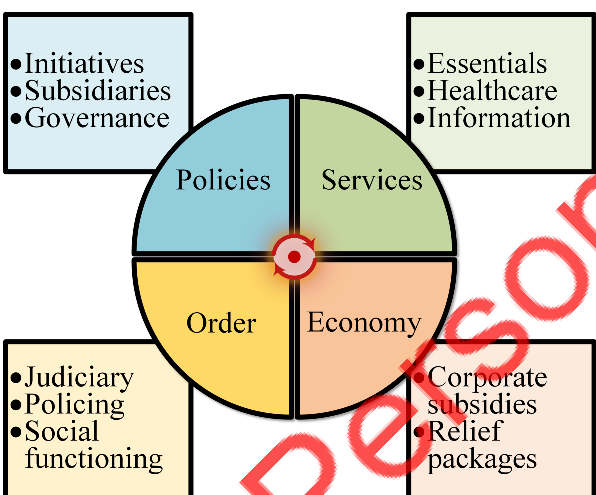

Fig. 8: Governance issues having a direct impact due to COVID-19.

challenges in the manufacturing and food industries, followed by supply logistics and e-commerce.

1) Manufacturing Industries: The manufacturing industry is one of the sectors that has been affected by the pandemic through multiple channels. With the prevailing lockdown, logistics and supply chain has been significantly affected due to the unavailability of transport, human resources, and market demand. In this remorse situation, the industries are expected to help their employees financially by avoiding layoffs and unpaid leaves.

2) Food Industries: Although there are no reports of COVID-19 spreading from food or water, the food industry is indirectly affected by other driving factors such as availability of raw materials, unrestricted mobility of public, and market demand [23]. The packaged food industry tends to suffer similar setbacks and challenges as the manufacturing industry.

3) Logistics and Supply-chain: Logistics and supply chain is one of the core sectors which maintains the inflow and outflow of materials during and post-production. The railways and roadways have been operating to ensure the supply of essentials and movement of people in emergency services. The effect of COVID-19 on logistics and supply chain has affected every element of primary and secondary sectors of the economy. [24]

4) E-commerce: E-commerce is one of the hardest-hit sectors during this pandemic. As transportation and logistics have been restricted, the delivery of goods has been affected. Almost all the e-commerce websites had to stop their services during complete lockdown phases. Most online platforms providing groceries and other basic amenities were allowed to operate under many restrictions in selected areas.

E. Public Gatherings

Meetings and gatherings are significant facilitators in making essential strategies and decisions. However, they are also facilitators for spreading the virus and infecting healthy individuals in pandemic-like situations. In this section, we highlight some of the challenges in activities that involve gatherings and meetings.

1) Education: As the educational institutes have crowded classrooms with children and have common facilities to share, COVID-19 is likely to spread at a much faster rate. Regular classes have been suspended, and exams have been postponed. Online education platforms, collaborative work platforms, and video-audio conferencing tools have seen a surge in their usage as these are the means to shift the regular classroom education to personal rooms and homes.

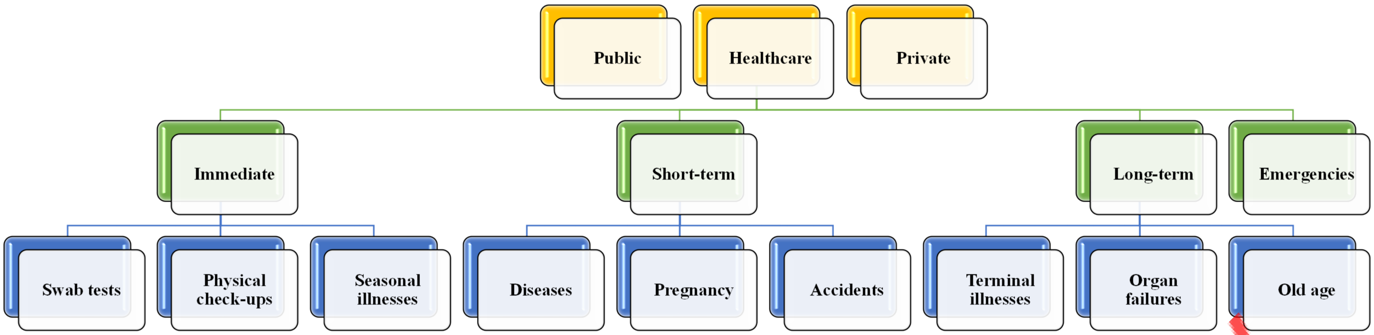

Fig. 9: Components of Healthcare.

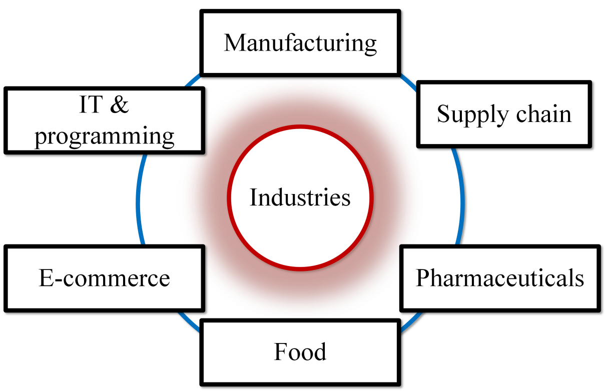

Fig. 10: Types of Industries.

2) Corporate meetings: The corporate culture has adapted to its work-from-home policy as the new normal, which was otherwise considered as a privilege. Online conferencing tools such as Google Meet, Zoom, and Cisco Webex have been supporting virtual online meetings, which also raises many security and privacy concerns.

3) Social Engagements and Interactions: Society, as a whole, is disrupted with the outbreak of COVID-19 around the globe. Social distancing is being considered the most significant measure against preventing the spread of the infection. Regulations have been put in place to limit the number of persons participating in public gatherings and private family functions.

III. IoT Networks and Architecture

In this section, we briefly present some of the basic concepts of IoT and its modes of operation. The IoT architecture usually consists of three layers (Fig. 11) with the end-users and sensors at the bottom, a network layer in the middle (including edge and fog devices), and the cloud at the top. In the subsequent sections, we briefly describe some of the popular IoT methodologies.

A. Cloud, Edge, and Fog

The cloud computing paradigm offers remote on-demand services, which typically include Software-as-a-Service (SaaS), Platform-as-a-Service, Infrastructure-as-a-Service (IaaS), and others. These services are dedicated to offering virtualized platforms to users with varying levels of interventions. The cloud usually consists of high-performance devices, which include servers, data centres, and supercomputers. However, as shown in Fig. 11, the cloud computing paradigm incurs high transmission delays where edge/fog computing paradigms help in overcoming such high latency [25]. These paradigms bring the services of the cloud closer to the end devices (users and sensors) at the edge of the network. Fog computing depends on the cloud for storage and complex analytical operations on getting overloaded. Strategic solutions help in identifying the priority of the tasks (based on application type and deadlines) and in making decisions on forwarding it to the cloud or on-site.

B. Local versus Remote Processing

End devices usually consist of both resource-constrained and resource-rich devices, which may or may not be mobile (including both users and sensors). The designated applications may also vary based on their type and delay tolerances. Under such circumstances, strategic decisions on where to perform the computations on the incoming data are necessary. The strategic decision is made to leverage each of the layers in Fig. 11 with its own set of advantages and disadvantages. The quality of the services may vary depending on the location, intermittent network conditions, bottlenecks, denial of services, delay-sensitivity, and others. During heavy traffic and unprecedented conditions, it is beneficial for the end devices to perform the necessary operations on-board instead of offloading it to the external platforms.

C. Centralized versus Distributed Processing

Centralized systems locate major components necessary for execution on one primary site. While such systems simplify setup, management, and execution, it suffers from a single point of failure, denial of service, bottlenecks, scalability, and limited backup when compromised. Decentralized systems distribute authority, components, and operations across different locations and devices. It offers higher scalability and resistance to issues mentioned in the case of centralized systems. However, it suffers from setup and management complexities, which requires strategic solutions for coordination. Decentralized systems are also dependent on the network conditions as they pass control messages from one device to another.

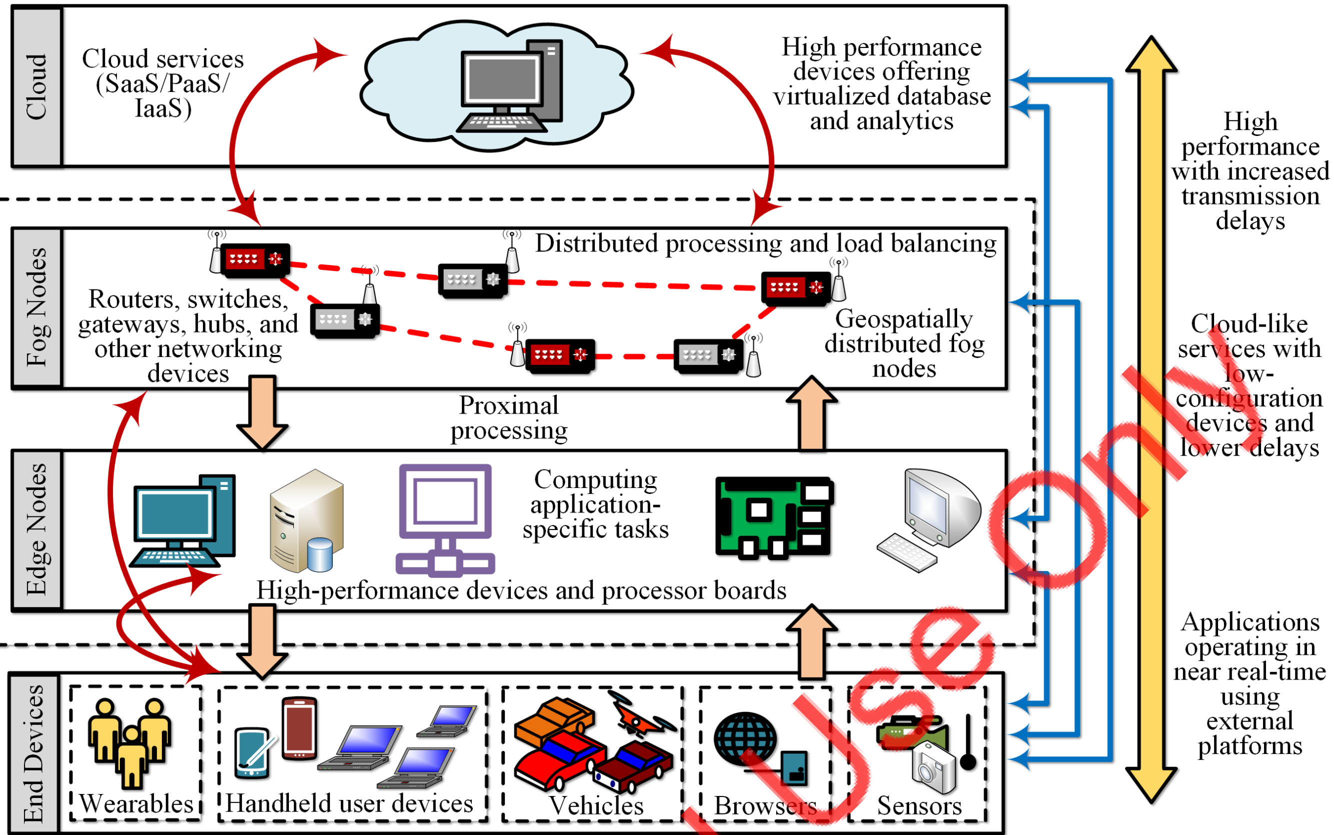

Fig. 11: IoT networks and architecture with different operation modes.

IV. Challenges in Conventional IoT Technologies and Applications

IoT-based solutions have been in use in different domains, such as mentioned in Section II. Most of the available solutions are either in the form of smartphone applications or devices with integrated sensors. In this section, we categorize the existing IoT technologies and applications in 8 broad domains, as shown in Fig.12, and present the limitations and challenges faced in these domains during the pandemic.

Vehicular networks	E-health	Big data	Machine learning
•Confined space •High-density crowd •Multiple surfaces •Dense fomite spaces	•Unavailability to routine visits •Contamination •Remote diagnosis and treatment •Disruption of clinical field trials	•Privacy concerns •Varying governing laws •Consent gathering	•Data-driven •Lack of datasets •Changing scenarios •Obsolete models •Rigid
Smartphone networks	**Computer vision**	**Device development**	**Telehealth**
•Data security •User privacy •Consent gathering	•Lack of datasets •Establishment costs •Issues analogous to machine learning	•New designs •Establishment costs •Contactless designs •Procuring raw materials	•Training doctors and patients •Resource/infrastructure unavailability •Coordination for availability

Fig. 12: Challenges in the current IoT infrastructures.

A. E-health

E-health is one of the primary domains that will boost and need further development in the future. In the present scenario, social distancing and restricted movement are the only criteria preventing the spread of COVID-19. Hospitals have been closed to routine visits and addressing only COVID-19 infected patients and emergency cases. Due to the ongoing COVID-19 treatment at the hospitals, there is a fear of contamination, and it is not safe for other patients to be in and around the hospital infrastructure. As a result, the health sector has to find alternate means to provide remote services to the patients in need of diagnosis and treatment. E-health services such as remote doctor consultations, remote patient monitoring, and remote diagnosis of diseases can be utilized to provide healthcare services to the patients, also including the rural and hard-to-reach areas. However, with an increasing number of e-health solutions being developed, these solutions need to be tested and validated through clinical field trials under experienced supervision. These clinical field trials are temporarily unavailable due to the pandemic, which may either slow down the process of device and system validations or may risk the patient's health with scientifically inaccurate devices. Developing new systems and technology will require financial assistance, which can be an additional challenge during COVID-19 due to the current economic crisis [26]. Also, the implementation of large scale e-health solutions is prone to additional network and communication failures.

B. Big Data Analytics

Big data is a massive source of demographic and geographical information. In terms of COVID-19, big data generated by mobile phone users and m-health devices can be used to track infected patients, trace their movement, and predict any possible outbreak in a region. Big data is being used to predict the pattern of the outbreak, estimation of peak cases, duration of a wave, and the cycle of infection. However, privacy is one of the major challenges faced by big data acquisition and analysis. Different governing laws in different countries legally protect access to personal and sensitive information. This personal information may be required for tracing the infected patients, such as the patient identity, identity of people connected to the patient, movement of the patient, and other such information. The governing agencies must ensure that such sensitive information is handled with care and used strictly for non-commercial purposes [27]. Acquisition of personally identifiable data from the public must be informed beforehand and asked for their consent, which poses another challenge towards using big data for COVID-19 tracking and prediction. Another application of big data is to derive the relation between COVID-19 and other diseases such as symptoms, the possibility of infection, the effect of the infection when combined with other medical conditions, and others. This would require access to public health medical records, which is considered private and needs to be highly secured.

C. Machine Learning

Machine learning uses input from the surroundings to learn things and make decisions based on learning. Every change in the environment affects decisions such as diagnosis, prediction, and recommendation offered by an application using machine learning. While the world is still struggling to cope with COVID-19 and its effects, applications with machine learning algorithms are no exception to this novel situation [28] [29]. Various industries used machine learning algorithms to enhance their production, security and decide their production and marketing strategies. As the socioeconomic arrangement is disrupted by the pandemic, the changes have resulted in insufficient or logically incorrect data for machine learning models. Industries that are dependent on medium to small learning cycle span ranging from hours to days are sensitive to small changes in the application domain [30]. Examples of such industries are stock market estimations, the recommendation of products on e-commerce platforms, forecasting market demands for manufacturing industries, and inventory management. These current changes in the learning data lead to disordered A/B testings through context manipulation by precarious data entries. The previously trained models used in different industries are programmed to detect any unwanted changes or anomaly by historical data analysis, trend analysis. With unprecedented changes caused due to COVID-19, the machine learning models may suffer ”concept drift” where the model may misinterpret a situation or output as an anomaly [31]. Many production units, logistics, and supply chain operations are temporarily nonoperational. This is likely to result in missing time series data, which is used by machine learning models in forecasting, recommendation, and optimization applications. Manual interventions and updates are required in industrial applications of machine learning to accommodate the unexpected changes in user behaviour and market response. It may also require training of the existing models with the new data to address and include these changes.

D. Smartphone Networks

Smartphones are being utilized to enable two major tasks to handle the effects of COVID-19 – 1) contact tracing and 2) Detection of infection [32]. The detection of infection is further divided into individual health parameter tracking through smartphone embedded sensors, identification of possible clusters and hotspots in a region through survey-based mass data collection, and access to web search history. Contact tracing has proved to be one of the most common and effective applications of smartphones to contain the spread of COVID-19 infection. Many smartphone applications have been developed to enable contact tracing and tracking of suspected infection outbreaks and hotspots. Contact tracing helps in notifying the users of any possible contact or a random encounter with infected people. This data is analyzed using machine learning algorithms such as k-means clustering to make different predictions about the spread of disease and its pattern based on user locations and movement. This information can be used by different authorities and organizations to plan the lockdown [33]. Mobile applications are used to collect self-reported mass data from the public, such as age, gender, symptoms, previous medical history, and analyze the data using machine learning techniques to predict the likelihood of a patient being infected [34]. This data is also used to derive the relation between different physiological conditions and the infection to ultimately detect the infection in an individual. However, studies have been conducted to evaluate the effectiveness of smartphone-based contact tracing in the case, suggesting that smartphones may not be able to trace the epidemic during the first phase [35] [36] [37]. Works on evaluating and implementing data security and user privacy have been attempted. Multiple works suggest that Bluetooth-based communication for data collection through a mobile application is the most secure method compared to WiFi and other technologies [38] [39]. In view of the privacy and security risk associated with collecting location and personal data from users, checkpoint-based contact tracing has been proposed [40]. The embedded sensors from smartphones are being utilized to detect COVID-19 infection by analyzing the breathing sound and pattern in an individual [41].

E. Computer Vision

Computer vision, combined with complex and intelligent machine learning methods, are being used to detect the presence of COVID-19 infection in patients. Medical imaging such as X-ray and CT scans can utilize computer vision, image processing, and machine learning-based decision making to identify, delineate COVID-19 infection from any other illness and make clinical inferences [42]. Machine learning-based processing of X-ray images has been found to be useful in differentiating pneumonia caused due to COVID-19 and normal pneumonia using techniques such as Deep Convolutional Neural Networks (CNN) [43] [44]. Capsule Network (CapsNet) are used to derive the spatial relationship between different instances of X-rays to work with smaller datasets [45]. New pre-trained frameworks have been built and tested, such as COVIDX-Net, to aid radiologists and doctors with automatic detection of COVID-19 infections [46]. Additionally, CT scan analysis has also proved to be efficient in detecting the infection by using features extraction and classification methods in machine learning [47]. Crowd surveillance and social distancing can be efficiently implemented and followed using computer-aided vision and image processing. Object detection, classification, and localization techniques using deep learning frameworks have been proposed [48].

F. Device Development

The availability of protective gear and masks such as Personal Protective Equipment (PPE) kits and N95 masks has led to significant worry and chaos among the front line healthcare workers. In addition to the existing shortage of healthcare workers, the chances of these healthcare workers getting infected are higher with a lack of protective devices and gears. Smart PPE, such as smart helmet and smart protective suit have the potential of managing the spread of the disease through continuous monitoring of the persons vital parameters, the surrounding environment, and identify any threat. The infusion of IoT with PPE can reduce the response time and enable timely actions against any hazardous situation. Depending on the type of infection and the mode of transmission, various kinds of PPEs have been recommended [49] [50] [51]. COVID-19 has forced the device manufacturers to develop new designs and utility to make things work in times of pandemic. Contact-less temperature screening is one of the most essential and common featured devices that have been in use since the beginning of the epidemic. IoT-based smart helmet to monitor body temperature [52], contact-less infrared temperature sensing [53] are some of the devices that are being used to monitor the body temperature of an individual without the need for any physical contact. Different biosensors have been developed to identify the presence of SARS-COV-2 in the clinical specimen. Field Effect Transistor (FET)-based biosensor is proposed and tested for swab test analysis of SARS-COV-2 [54]. These biosensors are highly sensitive and can provide instant real-time diagnosis, making them useful in point-of-care devices and on-spot detection of infection [55] [56]. Point-of-Care (PoC) devices aim to perform diagnostics methods such as pathological tests and clinical examination on the data collection site itself, eliminating the need to send the data or biological samples to remote laboratories. PoC devices, in combination with IoT devices, can be used to diagnose and monitor the patients in quarantine [57]. PoC devices will allow patients to self access their medical conditions and possible infection, which will reduce the response time and also help in containing the infection with prior information and reduced human interaction.

G. Telehealth

Telehealth has redefined healthcare services that need to be implemented in our routine healthcare [58] [59]. Telehealth aims to provide healthcare services, both clinical and non-clinical, in a remote location with minimum physical contact. Telehealth utilizes digital tools and technologies such as audio and video conferencing, IoT-based remote monitoring, and others.

TABLE II: IoT technological aspects as possible solutions for various COVID-19 affected modern societal components.

Domain	Governance	Industry	Healthcare	Transport	Tourism	Education	Social Engagements
Vehicular Networks	X	✓	✓	✓	✓	X	✓
E-Health	X	X	✓	X	X	X	X
Big Data	✓	✓	✓	X	X	X	X
Machine Learning	X	✓	✓	X	X	X	X
Smartphone Networks	✓	X	✓	X	X	✓	✓
Computer Vision	✓	✓	✓	✓	✓	✓	✓
Device Development	X	✓	✓	X	X	✓	✓
Telehealth	✓	✓	✓	X	X	✓	X

As COVID-19 continues to spread through human contacts and fomites, it becomes important to avoid physical contacts as much as possible, especially in hospitals and the clinical environment with higher infection risks. With rapidly increasing infection, healthcare workers are also at greater risk of getting infected, eventually decreasing the number of doctors and caregivers for the increasing number of patients. Adoption of telehealth services on a global level is the most efficient way to prevent the spread of COVID-19 through highly infectious environments and, at the same time, maintain the regular healthcare services [59] [60] [61]. Studies show that the usage of telemedicine has been accepted well by the users and proved to be highly effective during the COVID-19 outbreak in different parts of the world [62] [63]. In view of enabling telemedicine services, many devices have been proposed and implemented for remote clinical analysis such as smartphone-based wireless otoscope [64], smartphone-based remote dermatology consultation [65].

However, telemedicine implementation also poses challenges such as training healthcare professionals, availability of resources, and infrastructure to enable remote access and creating awareness among the patients and individuals about the benefits of telemedicine over traditional healthcare services [66]. Table II summarizes the possible IoT domains which can serve as solutions to the COVID-19-affected application areas.

V. IoT to the Rescue

IoT plays a vital role in the prevention, diagnosis, and control of the severe damage caused due to the outbreak of COVID-19. The genesis of COVID-19 can be traced from an infected individual to the community, group, and public places. At each level of infection- individual, family, community, public - IoT offers different solutions to predict, reduce, and contain the infection (Fig. 13). Some of the popular IoT-based solutions that have been developed to manage the COVID-19 pandemic are presented in Table III. At individual levels, methods such as image, audio, and video analysis, remote e-health services, and smartphone-based diagnosis help minimize the risks associated with the disease. Families can use remote telehealth services,

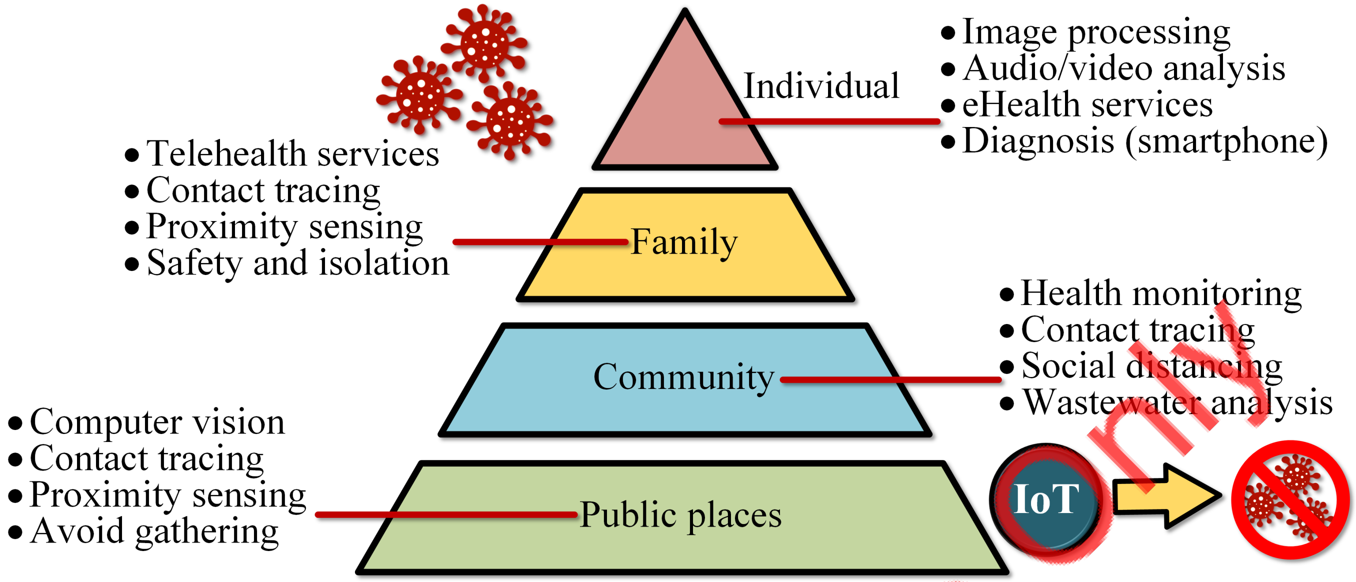

Fig. 13: IoT to the rescue at different levels in society.

TABLE III: Different commercially available solutions for control and mitigation of COVID-19 pandemic

Solution	Type	Objective	Region
Arogya Setu [67]	Mobile app	Contact tracing, local data analysis and diagnosis/probability of infection	India
Corona-Warn-App [68]	Mobile app	Decentralized contact tracing, alert users if they have been exposed to SARS-CoV-2 virus	Germany
Immuni [69]	Mobile app	Contact tracing, alert user about their exposure to SARS-CoV-2 virus	Italy
RadarCOVID [70]	Mobile app	Contact tracing	Spain
HaMagen [71]	Mobile app	Contact tracing, alert user about their exposure to SARS-CoV-2 virus	Israel
careFIJI [72]	Mobile app	Contact tracing, alert user about their exposure to SARS-CoV-2 virus	Fiji
TraceTogether [73]	Mobile app	Contact tracing, alert user about their exposure to SARS-CoV-2 virus, also includes a token system in the absence of a mobile phone	Singapore
GreenCode [74]	Mobile app	Contact tracing, online health status declaration	Israel
Libelium-Aridea Fever Screening Kit [75]	Monitoring device	Contactless, portable device to detect high body temperature at public places using infrared sensor	Global
EpiOneNG [76]	Monitoring device	Remote physiological parameters monitoring and analysis with local data visualization, reduce physical contact and visits to public hospitals and clinics	India
MySignals Kit [77]	Monitoring device	Remotely monitor more than 15 physiological parameters, reduce physical contacts and visits to public clinics and hospitals	Global

contact tracing, and proximity sensing to ensure safety and avoid any potential spread of infection by isolation. At the community level, IoT-based health monitoring, contact tracing, social distancing, and wastewater analysis are some of the methods that can help in the prevention and control of disease spread. Computer vision-based methods are implemented at the public level to ensure the practice of social distancing, identification of possible threats such as individuals without masks, proximity, individuals with symptoms can be identified and alerted in public spaces to avoid any community spread from public places and gatherings. Fig. 14 depicts some of the applications where IoT has the potential to make significant contributions to society. We identify the primary IoT-based methods for handling a pandemic, considering the case of COVID-19, in Table IV.

A. Mobility

Mobile and portable IoT-based solutions for COVID-19 play a vital role in point of care diagnostic systems, early warning, and prevention of infection, and containment of disease spread. The most trivial and commonly used example is portable thermal scanners to detect the body temperature of the human body. A Smart helmet with thermal scanning and facial recognition tracks body temperature and generates alert for any abnormal data using smartphones [52]. Smartphone-based contact tracking allows keeping a record of any possible close interaction with COVID-19 positive patients or travel history to any containment zone [36]. Identification of

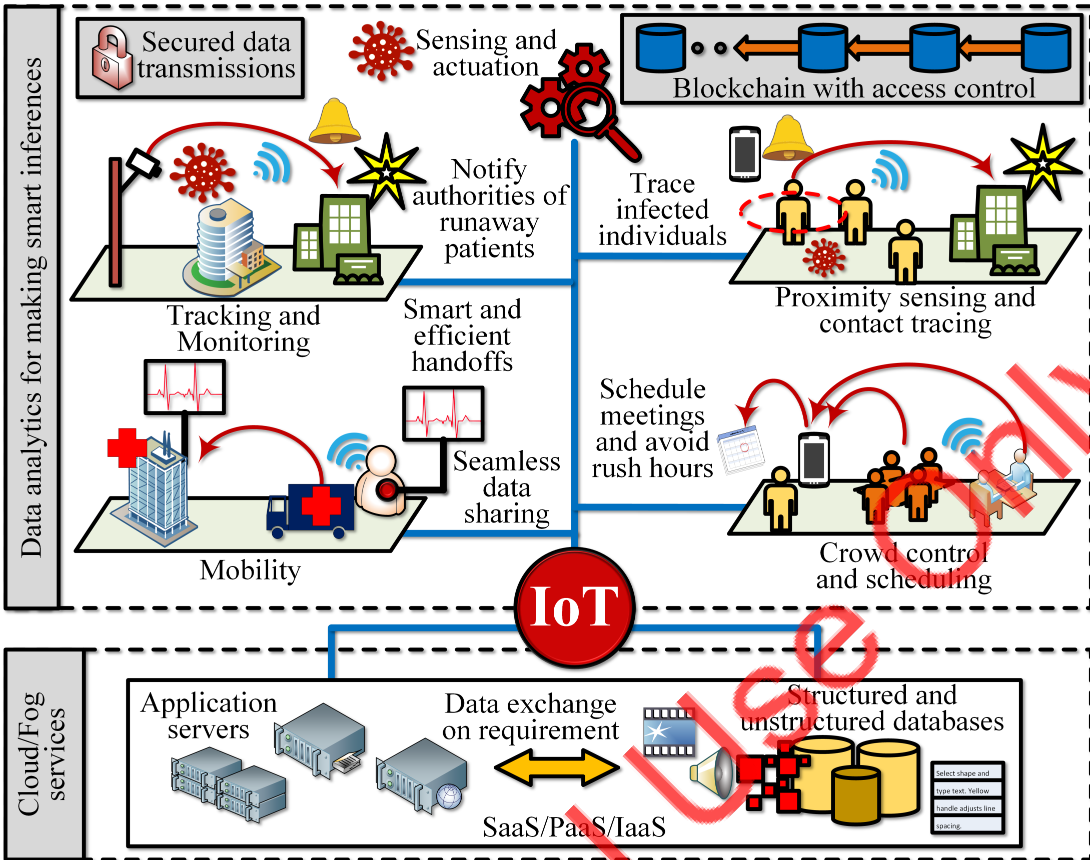

Fig. 14: IoT and its applications in combating COVID-19-like viruses.

TABLE IV: A Comparison of different IoT-based methods for combating COVID-19

Domain	Sensor	Evaluation Type
Mobility	Thermal scanner, Camera, Smartphone [52]	Preventive
Proximity	Bluetooth, WiFi, Smartphone, GPS [78], [79], [80], [81], [82]	Preventive
Crowd Control & Scheduling	Camera, Proximity [83], [84], [85], [85]	Preventive
Tracking	Bluetooth, WiFi, Smartphone, GPS, Camera [86], [87], [88], [89]	Preventive & Diagnostic
Monitoring	Camera, Smartphone, Biosensors [90], [91], [92], [89]	Diagnostic
Sensing & Actuation	Temperature, Camera, Actuators [93], [94], [95], [96], [97]	Preventive& Diagnostic

clusters of COVID-19 infection is an important method to mitigate the effects of disease spread. Smartphones provide a dynamic and mobile mode of community monitoring and surveillance through contact tracing, web search history, and trends [37]. Portable medical devices such as ventilators, remote health monitoring systems, and wearable devices help reduce physical contact with infected patients. These portable medical devices also help in facilitating regular health check-up through remote consultation [57], [98], [99].

B. Robotics

Robotics integrated with IoT-enabled systems have been used in different domains such as transport, logistics, ehealth, security and surveillance, and others [100] [101]. The pandemic has restricted human contact and interaction due to the contagious nature of the disease. While most of the industries saw a decline and halt in their supply chain and demands, the industries working with robotics saw an unusual increase in the demands for various type of robotic devices and machines. Robots with camera sensors and temperature sensors are being used to measure body temperature and detect if a person is wearing a mask, during their visit to hospitals and other public and private establishments. Particularly in hospitals, robots are being used for front line interaction with patients, to avoid direct contact between patients and healthcare workers [102]. Food and medicines delivery, taking swab samples of patients, and even friendly interaction with humans to compensate for the isolation are some of the popular domains which have used robotics to adapt to the perilous environment [103]. Drones have been found useful in contactless delivery, remote sanitization, thermal scanning and crowd monitoring during the pandemic for safety and disease prevention [104] [105].

C. Proximity sensing

Proximity sensing is one of the primary attributes of observing social distancing and contact tracing. Since the SARS-COV-

2 virus is expected to spread through infected respiratory droplets, maintaining social distance is the most effective way to reduce the spread without exact information of the infected individuals [78] [79]. Rigorous and extreme distancing methods such as complete shutdowns and lockdowns have adverse psychological, economic, and social effects. To curb these adverse effects, researchers have proposed creating a social bubble to control proximity and maintain normalcy. Simulations on Social network-based interaction have shown different strategies to implement the concept of social bubble and effectively reduce the virus transmission rate without completely prohibiting social contacts [80]. Proximity sensing in clinical environments such as hospitals and quarantine centres is also important to ensure the safety of healthcare workers. Studies show that real-time location tracking of healthcare workers during their interaction with patients can increase the efficiency of contact tracing and help identify workers at greater risk of acquiring infection [81]. Smartphone-based proximity sensing has been the most popular and widely used method because of easy access to smartphones. These mobile applications generally use Bluetooth based proximity detection from other devices in the vicinity or proximity. Any alert about the user's status of infection is shared anonymously across other users and alerted of any potential infection [82]. Personal log keeping applications have been proposed which can automatically log the activities such as mobility, visit different locations and social structures along with provision for manual entries such as any physical contact with a person, passing by overly crowded space, interacting with someone without protective gears [106]. This log may help people trace their activity and estimate their chances of infection. While the ease of availability and personal data collection through smartphone applications is being appreciated, the privacy and security concerns pertaining to the collected data and the individuals is unavoidable. Various methods have been proposed to secure the identity of the application users and preserve the privacy of personal data such as geographical location details [107].

However, it is difficult for the underprivileged section of the society living in congested arrangements such as slums, with inadequate communal spaces and hygiene to apply and follow social distancing [108].

D. Crowd Control and Scheduling

The crowd and human gathering are some of the most dangerous and potential hotspots for COVID-19 spread [109]. There are numerous events where a mass gathering has resulted in an increase in the spread and geographical expansion of the infection [110] [111] [112]. Places with high population density are at greater risk of acquiring and transmitting the infection [113]. Models and plans for accommodating a maximum number of people in a confined space such as malls, plazas, and buildings have been proposed. These models follow the minimum distancing rule and calculate the number of people that can be allowed inside the structure [114]. Crowd control and distancing in hospitals and other clinical setup play an important role in preventing infection and protecting healthcare providers. Modified Traffic Control Bundling (TCB) has been proposed to minimize the interaction between infected patients and healthcare workers through fomites in hospitals [83]. Scheduling regular social and economic activities that require physical presence is yet another method to eventually manage the crowd and maintain social distance while performing the activities to avoid a complete shutdown. Healthcare service providers such as hospitals, ambulatory services, and other clinical services were among the first to implement rotation-based duty scheduling to continue the services without risking the entire healthcare worker community [84]. IoT-based surveillance with the help of camera networks and sensor data fusion can be used to monitor the crowd in the confined place such as hospitals, and workplaces. IoT-based solution for avoiding crowded places or routes with possible contamination has also been proposed [115]. All possible precautions are being taken to manage the crowd and prevent community transmission and the spread of COVID-19. Table V provides a comparison of different methods for crowd control and scheduling in public and confined places.

TABLE V: Different approaches for crowd control and scheduling in different environment

Approach	Application area
Calculating number of persons allowed with social distancing	Plazas, malls, public offices, and other confined places
Modified Traffic Control Bundling (TCB)	Hospitals and clinical setups
Minimizing workforce by rotation-based work schedules	Offices, hospitals, manufacturing units, and other establishments with multiple persons working simultaneously
Alternate days operation	Public places such as markets, places of religious interest, educational institutions
Remote work	Work which do not require physical presence such as IT, banking, teaching,

TABLE VI: Different methods for IoT-based tracking to mitigate COVID-19 infection spread

Objective	Method
Track social distancing	Smartphone-based tracking [36]
Proximity sensing	Smartphone-based sensing, Bluetooth proximity sensing, SMS-based alert system [82]
Contact tracing	Real-time locating system, tracking of healthcare workers [116]
Decentralized proximity tracing	Privacy protected tracing, identity preserving, proximity contact tracing [107]

E. Tracking

The number of patients with COVID-19 is increasing at a very high rate. Individuals with symptoms are being subjected to quarantine and hospital isolation. Many cases have surfaced where patients with suspect or positive COVID-19 have tried to flee the institutional quarantine and hospital isolation wards [117], [118]. Such cases create a state of panic and pose a threat to society. It is important to carefully track the COVID-19 suspects and patients and monitor them closely until they are fully recovered. Also, tracking the patients would enable them to identify the possible infection zones and provide safety and extra care to the healthcare workers coming in contact with the patient. RFID-based tracking can be used to track COVID-19 patients, trace their contacts, services, and objects used by the patients, and other medical waste generated. This information can help avoid further spread of the infection [116]. Mandatory wristbands have been provided for quarantine individuals to prevent them from moving beyond the quarantine zone and geo-fencing them [86].

Smartphone-based geo-fencing has also been implemented to track COVID-19 patients and suspects in quarantine and alert the authorities in case of any violation [87]. Other methods to ensure the home quarantine rules are uploading pictures of individual at regular interval at the same location with date and time, mobile phone applications with QR code scanners to avail any public facility and space so that any infected person does not contaminate the facility [88]. Table VI shows different methods of IoT-based tracking for COVID-19 and pandemics in general. Data security and privacy of user/patient is an important concern that has been raised in many countries and on many platforms. Secured IoT communication framework for the COVID-19 modelling, monitoring and tracking ensures that the data is securely transmitted to the central location, without jeopardizing the privacy of the patients and users, along with COVID-19 state prediction [89].

F. Monitoring

Remote and continuous monitoring of COVID-19 patients is necessary to access the risk and health conditions and, at the same time, contain the spread with minimal physical contact. Telemedicine and IoT-based systems can enable remote and continuous patient monitoring, along with alert generation and primary decision-making abilities [119] [120]. There is an urgent need for integrating telemedicine with traditional healthcare services to cope with the increasing load on our healthcare services and infrastructure due to COVID-19 [121]. Online questionnaires to study the symptoms and other health condition of patients is proposed to monitor the status of COVID-19 infection in individuals. These questionnaires are carefully designed to assess the physical symptoms and trends among the community for mass surveillance [90]. In addition to the daily online questionnaires, the individuals are provided teleconsultations and text messages alert to patients under home quarantine [122]. Smart health monitoring systems have been proposed to track COVID-19 patients in real-time to enable remote ICU monitoring through a smartphone application and external CCTV installations [91]. Such setup allows healthcare workers to closely monitor critical patients without being physically present at the location, monitor and identify any abnormal readings in the patient's health parameters and alert the authorities for prompt action [125]. Monitoring patients with the potential risk of COVID-19 helps isolate the patient before clinical diagnosis and reduces the risk of transmission. Telehealth systems in hospitals have been developed to closely monitor patients with pneumonia by tracking their daily health status and response to the treatment [92]. This surveillance helps in identifying patients that have a higher probability of being infected by COVID-19. Wastewater epidemiology is another very efficient method to identify infection in a community or a geographic region, resulting in mass surveillance [126] [124]. The study of wastewater can reveal the presence of infection in a community and alert the community members beforehand. This alert can help in reducing the burden on the healthcare infrastructure and workforce by taking appropriate steps through remote consultation or telemedicine. Utilizing smart cities to gather urban health information and crowd behaviour can lead to a better and prior understanding of any health emergency and outbreaks [127]. Table VII compares some of the existing IoT-based methods for the monitoring of pandemics.

TABLE VII: Different modes and methods of monitoring of COVID-19 pandemic

Objective	Mode	Highlights
Patient monitoring	Local and remote	Smartphone-based symptoms analysis [122] and visualization, questionnaires [92]
Quarantine monitoring	Remote	Telehealth, teleconsultation [121]
Crowd monitoring	Local	Camera-based surveillance, social distancing monitoring [48], crowd sensing [123]
Community monitoring	Remote, laboratory examination	Online questionnaires, symptoms and trend analysis [90], wastewater analysis [124]

G. Sensing and Actuation

As COVID-19 spread through fomites, many systems and devices have been proposed to replace the normal daily activities which require touching inanimate objects and surfaces [128]. Elevators are considered one of the most dangerous space to be acting as fomite and transmit infection. The touchless operation of elevators has been proposed by using proximity sensors [93]. Proximity sensors to detect any violation of social distancing are proposed to maintain safe distance [94]. Contactless infrared temperature sensors have found wide use during this pandemic to measure body temperature. Automated systems for remotely monitored hand sanitization systems in organizations with employees resuming their work has been proposed [95]. Various biometric touchless contactless devices have been designed and brought to use in countries like China, Japan, the US, Vietnam, and others [129]. A camera network with thermal imaging is used to detect human body temperature in masses. These systems can generate an alert if any individual with a high temperature is encountered. Facial recognition has played an important role in detecting any violation of social distancing and public hygiene, such as detecting faces without masks, the distance between individuals, and person identification. Governments have also used camera networks to detect and estimate any human displacement or movement across specified regions to control the spread [129]. Camera networks, along with mask detection and distance estimation, have been implemented in industrial setup to maintain the safety of the workers returning to work post-COVID-19 lockdown [96]. The ability of Unmanned Aerial Vehicles (UAVs) to traverse areas that are inaccessible by humans make them the ideal carrier to monitor a community or region that may be under the high-risk zone or a hotspot for COVID-19 spread. Remote areas with minimal connectivity and resources may utilize UAV networks and services to collect WBAN data from a community and assess the health situation [97]. Based on the health condition, UAVs may be equipped with thermal cameras, facial recognition tools to implement mass surveillance. We list some of the implemented and proposed solutions with sensing and actuation mechanisms in Table VIII. Transportation systems can use a different set of sensors and actuation techniques to reduce the surface touching, such as weight or proximity sensor-based door operations [131]. Airports and similar public places can use proximity sensors to operate washrooms, elevators, and point of sale units to minimize physical interaction.

TABLE VIII: Different sensing and actuation devices for COVID-19 diagnostics and mitigation

Device	Sensors	Objective
Intelligent PoC device	Biosensors	PoC diagnostics [56] [99], [98]
Drone	Camera, actuators	Detect unmasked person, alert local authorities, deliver masks [97], [130]
S2D	Proximity sensor, alarm	Detect and alarm social distance failure [94]
hand hygiene system	Ultrasonic sensor, camera	Touchless sanitizer dispenser, social distancing [95]
CCTV-based monitoring	Camera	Detect safety violation in factory setup [96]
Smart helmet	Infrared sensor, camera	Measure body temperature [52]

H. Analytics

Data analytics has become one of the most promising methods to estimate, understand, and predict the current unrest and chaos caused due to the outbreak of COVID-19 [132] [133]. From analyzing the epidemiological data of different population [134] to studying the serology of the virus, predicting the interaction of commercially available vaccines with the virus [135], and detection of the infection in patients [136] [137], all of these objectives are being achieved with the help of data analytics based on machine learning, deep learning, and AI tools [138].

Data analytics is the driving force behind the technologies used to combat COVID-19 effects. Applications such as facial recognition, detection of infection through analysis of CT scans, and X-rays use data analytics to design their models. Large scale data collected from the masses through questionnaires, online sessions, and mobile applications are used to predict and detect any possible hotspot or community at risk. Mathematical models such as the stochastic transmission model are used with real-life data collected from the public to identify the pattern of disease spread and predict new outbreaks [139]. Governments have used their national health data, information of immigrants, and their travel history to identify potential COVID-19 transmitters. Their clinical visits have been monitored, and alerts were generated for symptomatic patient [140]. Drug repurposing is a method to find a new application of an existing approved drug available in the market. As COVID-19 continues to spread at an alarming rate, and no vaccine has been successfully formulated and tested yet, drug repurposing can be an alternative method that may produce a positive solution against the infection. Data analytics and machine learning methods such as deep learning and CNN have been proposed to simulate the interaction of existing drugs with the SARS-COV-2 virus to find a cure or reduce the effect of infection [135]. Table IX shows a comparison of different data analytics methods and tools used for combating the effects of a pandemic.

TABLE IX: A comparison of data analytics methods for COVID-19

Method	Data Type	Objective
Deep learning	Image, statistical data	Diagnose, drug-target interaction [136], [135], [133], [42], [45]
Mobility model	Statistical data	Predict disease spread [139]
Computer vision	Image, video	Social distancing, preventive and control measures [48], [123]
Smartphone	Multimedia, location, proximity, questionnaire	Infection prediction, diagnosis, contact tracing [61], [33], [35] [36] [37]

VI. Discussion

In this section, we summarize the highlights of the IoT solutions and their role in pandemic-like situations in terms of their advantages, limitation, and future scope.

A. Advantages

We outline the features of the IoT solutions and present their role on a global scale in combating the COVID-19-like viruses while contributing to the steps towards returning normalcy to society.

- ***Ubiquitous and Pervasive Devices:*** IoT services typically include devices ranging from handheld mobile phones and surveillance cameras to high-performance cloud servers. Such devices are in abundance, and IoT enables seamless connectivity irrespective of the brand, data type, and applications. The pooling of these devices for collaborative and distributed execution of complex operations helps in achieving surveillance, contact tracing, knowledge transfer, and others.
- ***Low Cost and Form Factor:*** Most of the available devices in IoT are targeted towards enhancing user experience and include smart wearables, smartphones, and other handheld devices. Manufacturers are constantly dedicated to reducing the size and cost of capturing the market in addition to simplifying operation modes, coupled with services from the cloud/fog/edge computing platforms. These factors help in adding more devices to the ground and making the public aware of pandemic-like viruses and how to deal with them.
- ***Mobile and Easily Deployable:*** IoT devices consist of both stationary and mobile devices. Mobile services facilitate monitoring individuals in-transit with seamless data transfer methods. Moreover, features such as Over-The-Air (OTA) updates help in adding necessary features

on-demand. With features such as low power and low form factors, these devices last longer and are easily deployable. Further, simplicity in designs also reduces the cost of training individuals for using the devices on-site.

B. Limitations

Although we highlighted some of the advantages of IoT and its applications in Section VI-A, it suffers from a few challenges. The following are some of the limitations of IoT in the current scenario:

- ***Intermittent Network Connectivity:*** Both urban and rural suffer from connectivity issues due to different reasons. The urban areas have high interference due to restrictions from non-Radio Access Networks (RAN) friendly infrastructures. On the other hand, rural areas suffer due to a lack of access points. Moreover, highways also suffer from connectivity due to long stretches. Further, upcoming technologies such as 5G/6G communications have low transmission ranges, making deployment challenging in the current scenario.
- ***Deteriorating Economy:*** The disruption of industries, transportation of raw materials, manufacturing process, and others have led to the loss of jobs on a global scale. Due to such conditions and payment cuts, not all individuals can afford IoT solutions during pandemic-like situations.
- ***Deployment:*** Due to lockdowns and restrictions in travel, deployment is another issue in IoT solutions. Power supply, positioning, compatibility with existing infrastructure requires manpower for the initial setup.
- ***Untested Solutions:*** In terms of the data analytics and machine learning for identification, prediction, and solution to the pandemic, the quantity, and quality of data required is not sufficient. The existing solutions are highly data-centric and are not suitable in the current scenario due to the novelty of the COVID-19-like viruses. Further, data acquisition in times of pandemic poses challenges such as public response, privacy and security, accuracy, and meaningfulness [141]. Multiple ethical limitations and challenges are associated with technologies such as contact tracing, web search content tracing, and alert generation [142].

C. Future Scope

Taking into consideration the current limitations in Section VI-B, these are some of the IoT-based solutions that have the potential of overcoming them:

- ***User Provided and Opportunistic Networks:*** In the context of intermittent communication links, it is necessary to develop reliable communication schemes. The link breakage leads to packet loss and undesirable delays. User Provided Networks (UPNs) [143] may be helpful in the urban areas due to the availability of ubiquitous handheld devices. On the other hand, the same may not apply in the case of rural areas. In scenarios that lack access points and the possibility of UPN, we suggest adopting opportunistic networking-based solutions [144]. These solutions help in dynamically establishing communication links and also switching between different modes.
- ***Low-Cost Solutions:*** The deteriorating economy is a major concern, especially for adopting IoT solutions. Such conditions further necessitate the need for developing low-cost devices. Manufacturers need to develop new hardware designs that may help in achieving this. Designs that involve low power consumption peripherals are also desirable. Further, techniques such as sensor virtualization [145] may be beneficial for both sensor owners and customers. Moreover, service providers should aim for minimal profits during pandemic-like situations.
- ***Minimalistic and User-Friendly Designs:*** During pandemics, it is challenging for personnel to travel for deployment purposes. Under such conditions, it is beneficial for manufacturers and service providers to develop solutions with minimal complexities. The deployment should support easy plug and play. In case it is not possible, online training using both AR and VR technologies is a possible solution. It is also possible to hire local third party vendors for coordinating and assisting the deployments on site. Over the Air (OTP) updates are also helpful in making software-based modifications to the hardware.
- ***Crowdsourcing:*** As mentioned in Section VI-B, the current AI/ML techniques are data-driven. As the pandemic has brought major changes to lifestyle and society, existing pre-trained models may not be suitable for making inferences, which mandates the need for new models. However, collecting new data is challenging. Under such conditions, crowdsourcing is a viable solution. Depending on the developers, the crowdsourcing scheme may be either paid or voluntary.

Apart from these, the IoT domain is a subject of constant research, and there exists the possibility of coupling a few technologies with IoT for enhancing its features. The following highlights some of the technological trends that may be useful in pandemics:

- ***AI/ML-Based Solutions:*** Although AI/ML-based methods have their limitations and have been around for quite some time, it is a promising technique for making in-depth inferences and decisions. It detects the changing behaviour of both devices and humans for proactively making necessary changes. ML methods find scope in service predictions, fault detections, monitoring applications, surveillance, contact tracing, social computing, and others. In our opinion, as software, they are the basis of solutions for combating pandemics, starting from its inception to the end.
- ***Automation:*** Most infrastructures are not communicable by employees during pandemics and lockdowns. Under such conditions, normal functioning is important. Automation plays an important role as it overcomes the dependency of human interventions. The machines may exchange messages and make decisions based on the AI/ML models mentioned earlier. Although true automation is challenging, some of the applications are already

in place. For instance, replying to emails, application and data interpretation, data analysis, transaction processing, robotic arm movements, and others. Additional research for refining these and new solutions are important.

- ***Fog/Edge Computing:*** With the development of ubiquitous and low-cost devices, the configuration, storage, and battery capacity will go down. The devices need to offload processing to external platforms to overcome such limitations. While the cloud is a promising solution, it induces significant delays, typically for data transmissions. Fog/Edge computing offers better performance in terms of delays and throughput as it performs processing near to the data generating devices. Resource orchestration is necessary for optimized management and seamless service delivery. It also helps in enhancing data security as it does not involve transmissions over long distances.
- ***Blockchain:*** Blockchain inherently offers data immutability, transparency, distributed architecture, and security. Blockchains coupled with encryption methods may be used to store sensitive information, which may be decrypted only by the intended users. Additionally, selective data may be broadcast to the end users using blockchain while avoiding infodemics. Avoiding infodemics is necessary in pandemic situations to avert panic in society.
- ***Upcoming 5G/6G Technologies:*** These communication technologies have the potential of facilitating real-time data transmissions, which enables seamless connectivity. Further, it is a primary enabler of real-time virtualized applications, such as remote surgery, monitoring, and others.
- ***Augmented/Virtual Reality Solutions:*** Both augmented and virtual reality systems help interact with the real-world using visual and audio-based technology. These solutions, coupled with the previously mentioned 5G/6G technologies, help in achieving remote access to real-world objects in real-time.
- ***Software Defined Networking (SDN):*** SDN methods help in separating the control and the data planes. These solutions have the potential to enhance the micro-services pertaining to combat the COVID-19-like pandemics without accounting for the networking parameters and corresponding challenges.

VII. Conclusion

In this work, we presented a comprehensive study of the effects of COVID-19-like pandemics on various sectors of the societal-fabric. We highlighted the ramifications of the virus on societal pillars such as IT and programming, travel and tourism, industries, social gatherings, and others. We also presented how institutions such as the government, healthcare, and pharmaceuticals play a major role in returning normalcy and order in such situations. We then briefly presented some of the basic concepts of IoT and its modes of operation. Additionally, we presented how the current IoT infrastructure falls short in addressing novel pandemics. We accounted for such challenges and suggested feasible methods for deploying IoT solutions towards combating the virus. In summary, we presented this work as an attempt to provide a guideline for tailoring the current IoT solutions towards accomplishing societal needs and help in resuscitating from the current situation.

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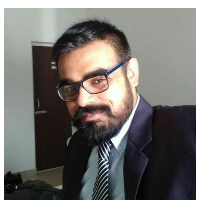

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