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Review Article

On revisiting vital signs IoT sensors for COVID-19 and long COVID-19 monitoring: a condensed updated review and future directions

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Abstract

Background: Although the world has been facing the COVID-19 pandemic for over a year, we understand that there are still some challenges in using Internet of Things (IoT) devices as allies in this fight. Among the main difficulties, we can mention the selection of appropriate devices and the correct measurement and subsequent analysis of previously obtained vital signs.

Methods: In this context, we present a condensed compilation of IoT devices to monitor the vital signs often used to monitor COVID-19. We focus on easy-to-use devices currently available on the market to the general user. Also, the presented analysis is helpful for long COVID-19 monitoring, which is particularly useful to governments and hospitals to analyze eventual sequels on those citizens who tested positive beforehand.

Results: The review resulted in 148 heterogeneous devices offering different capabilities. Our first contribution resides in detailing several aspects of each IoT device, indicating which are the most suitable for particular use-case situations. Moreover, our article introduces some challenges and insights into assembling a smart city composed of IoT devices.

Conclusion: Here, technological trends such as Serverless computing, homomorphic cryptography, Federated Learning, Elixir programming language, Web Assembly, and vertical elasticity are discussed towards enabling vital sign-driven data capturing and processing. Although there are several IoT devices for health monitoring, there is still work to standardize data formats and APIs for data extraction.

Keywords: COVID-19, Vital Signs, Internet of Things, Smart City, Wearables, Smartwatch, Brazil

Background

Coronavirus disease (COVID-19) was first identified in 2019 in Wuhan, China, and has since spread to other world regions [1]. The World Health Organization (WHO) declared the situation a pandemic on March 11, 2020 [2]. In this scenario, the COVID-19 pandemic brought many challenges to the health system. Severe acute respiratory syndrome, caused by SARS-CoV-2 (severe acute respiratory syndrome coronavirus 2), occurs in more significant numbers due to the rapid transmissibility of the virus in the airways. Since the spread occurs at high rates, the control and observability of the pandemic situation are yet more important [3]. The virus can rapidly spread from person to person through droplets in the nose or mouth by coughing or sneezing. Thus, the demand for rapid screening and data collection to diagnose the disease as quickly as possible is very important but still precarious. Currently, five vital parameters can help monitor the COVID-19 evolution: respiratory rate, body temperature, heart rate, heart rate variability, and oxygen saturation. Traditionally, each parameter has its clinical measurement method, which requires the individual to realize specific exams. For some of them, such methods may not be practical. For instance, in remote monitoring, the individual would need to attach specific hardware to its body which is only available at hospitals. To close this gap, several Internet of Things (IoT) devices can continuously monitor all five vital signs using a single device with multiple sensors, such as smart wrist bands and smartwatches. Figure 1 illustrates the difference in hardware requirements between the different methods. On the one hand, traditional methods employ (i) strain sensors to track the breathings per minute (BRPM) by chest movements;

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(ii) electrodes attached to the chest in electrocardiography (ECG) to track heartbeats per minute (BPM) and heart rate variability (HRV); (iii) infrared or skin sensors to track body temperature, measured in Celsius (ºC), Fahrenheit (ºF), or Kelvin (K); and (iv) oximeters to track peripheral oxygen saturation (SpO2). On the other hand, a smartwatch equipped with multiple sensors can provide information to track all parameters at once. Wearable devices decrease patients' complexity, offering wireless connectivity to the rapid transmission of data in real-time. Moreover, smart wrist bands and smartwatches are becoming popular since they are widely available on the market at a decreased cost. Besides being easy to use, these devices do not require a specialist to configure them.

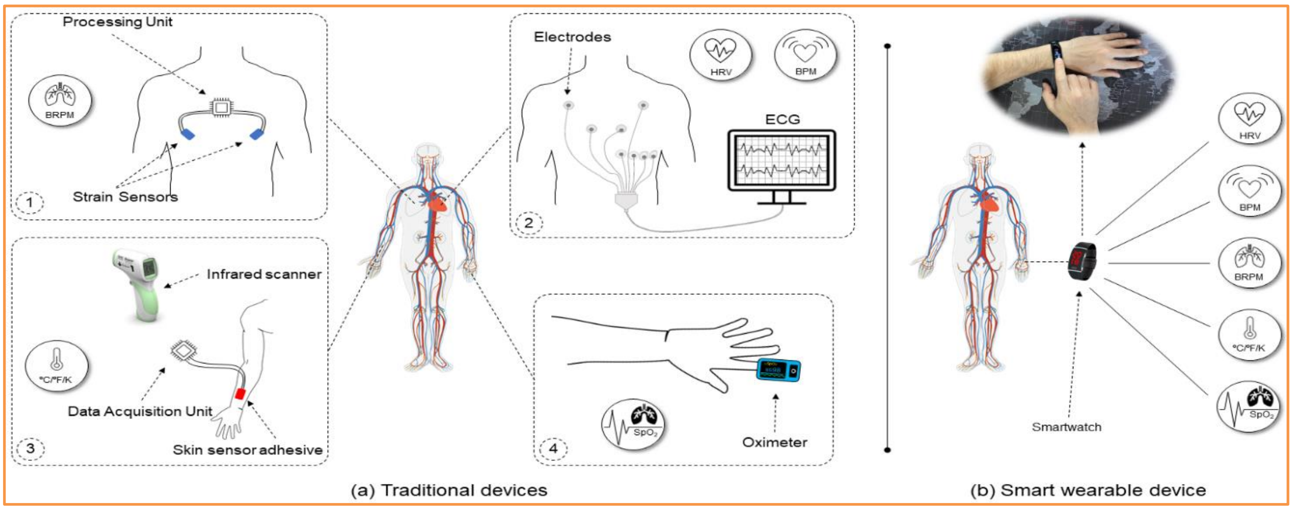


Figure 1: Traditional methods versus an integrated IoT device for monitoring the main vital signs forCOVID-19 diagnosis.

IoT can be defined as the interoperability of electronic devices through internet communication, being one of the most promising solutions for the health industry [4]. The use of IoT devices to monitor changes in vital signs can be a great ally in the early detection of infection [4]. It can reduce the spread of the virus and indicate the need for medical care before a critical situation occurs. Also, this kind of device can help governments and hospitals monitor those who had the symptoms of the virus, bringing new insights regarding eventual sequels on the long COVID-19 treatment process. The employment of such technology is capable of aiding patients to gain better control of their vital signs and medications, also providing a primary contact channel with physicians in critical cases [5]. In an IoT context, intelligent sensors are the essential tools to understand and analyze the environment. These sensors collect physical and analog data from the environment, digitalizing and processing them before sending them to an access point or the internet. They are minimally composed of sensor hardware, a micro processing unit, and a communication interface [6]. In particular, intelligent sensors capable of collecting vital signs, or mainly designed for hospital or clinic environments, are characterized as the Internet of Health Things (IoHT) devices [7]. As we can observe in the recent literature [4, 8, 9], research articles focus on tracking vital signs because the virus has a high propagation rate. Nevertheless, we perceive a lack of centering attention on the quality and the proper selection of devices to analyze such vital signs. Currently, to the best of our knowledge, there are no literature reviews that comprehensively and technologically cover the most critical IoT devices for COVID-19 monitoring. Dunn et al. [10] mention some devices applied to tracking vital signs in general. The article does not include technical details such as security support or API (Application Program Interface) compatibility. Ding et al. [11] present wearable devices applied to the COVID-19 pandemic. However, they do not show examples and brands of available devices on the market, not detailing security aspects and how to extract data. In turn, Nasajpour et al. [12] showed the application of wearables, drones, and robots in facing the COVID-19. However, they do not present technical details regarding the hardware employed, not presenting programming interface and interoperability issues. Thus, these articles only mention the lockdown efficiency, people tracking, and some scientific questions about the mutability of the virus; nevertheless, they do not have an updated vision of IoT technologies and how they can help monitor COVID-19. Considering the context, we envisage the need for a technical and theoretical study of IoHT devices that could be used to fight against the COVID-19 pandemic. We focus on wearable devices available on the shelf for the final customers. This article considers this panorama to present IoT devices, highlighting their pros, cons, and characteristics, including security, API, and SDK (Software Development Kit) support. This study aims to aid the academic, private, and public sectors by providing a deep listing of wearable devices capable of sensing vital signs. Also, different from related work, our contribution goes towards monitoring long COVID-19 by presenting devices that can be used to in-home sensing citizens and sending proper notifications to physicians and hospitals. Here, sequels and reinfection information serve governments and hospitals to tune health methodologies and budgets. Thus, this article can assist policies for geographical city control or population health monitoring. Finally, this work could help end-users and the scientific community by providing better decision-making when acquiring IoHT wearable devices. In addition to IoT information regarding vital signs capturing, this article discusses how a smart city would capture health data from all citizens, detailing innovations regarding data transmission and processing.

Vital Signs for COVID-19 Monitoring

Before getting immersed in sensors and devices, it is essential to understand the crucial health parameters that can help diagnose and monitor the progression of COVID-19. In the same way, the vital signs discussed here are pertinent to give us insights sequels regarding the long COVID-19, which is especially important for patients with chronic diseases. By analyzing the literature [4, 13, 14], five health parameters are the most striking vital signs to detect the evolution of COVID-19 (see Figure 1 for detail): (i) respiratory rate; (ii) body temperature; (iii) heart rate; (iv) heart rate variability; and (v) peripheral oxygen saturation. The following sections describe all the vital signs that help diagnose the COVID-19, briefly explaining how wearable devices can monitor them.

Respiratory rate

Respiratory rate is the ratio of breathings in a minute [15]. Usually, a normal respiratory rate fall between 12-20 BRPM. Shortness of breath is one of the early symptoms of COVID-19 [16]. COVID-19 may cause lung damage, leading the individual to rapid and shallow breathing, which indicates that the person has tachypnea. Consequently, the patient’s status is reflected directly in the patient’s respiratory rate measurements. Therefore, respiratory rate is a crucial health parameter for constant monitoring of COVID-19 infections. Nowadays, wearable devices can provide continual respiratory rate monitoring through piezoresistive and inertial sensors [17]. Most strategies require the placement of sensors in the patient’s chest, abdomen, neck, or nose. These are the most common strategies where studies employ new IoT technologies which are becoming smaller and less intrusive. Even though the sensors are becoming light and small, their placement can still displease on a daily-basis usage. Thus, new solutions arise on algorithms to derive the respiratory rate from optic sensors embedded in smartwatches and smart wrist bands. According to Fitbit (https://www.fitbit.com/), their smart bands and watches can measure this vital sign by the measured heart rate. The period between the heartbeats decreases during inhaling and increases during exhaling. Thus, the optic sensor of the heartbeat measures the slight differences between these periods while the user is sleeping to define the average respiratory rate of that night. The data acquisition process requires the individual to wear the device for at least three hours during the sleep night.

Temperature

Measuring body temperature is essential to monitor possible health abnormalities. According to Chow et al. [16], fever is the second most common symptom of a COVID-19 infection. In general, body temperature over 37.3ºC characterizes fever, indicating that the body is trying to fight an illness or infection [16,18]. Generally, body temperature can be measured axillary, orally, and rectally using traditional thermometers. However, recent solutions employ less intrusive technologies that can measure skin temperature. Different from the core temperature, the skin temperature frequently varies to regulate and stabilize the core temperature. More recently, the employment of imaging and infrared sensors became common to quickly check the body temperature of individuals in a touchless manner [19]. Also, studies and initiatives are constantly developing wearable technologies to monitor skin temperature. In general, such strategies apply skin carbon nanotube (CNT) printed adhesives that provide more precise temperature detection [20, 21]. However, CNT-based sensors require a computing unit to acquire data from the sensors to make them available for processing. This imposes complexity and a barrier for real-time temperature monitoring. As an alternative, smart band wearable devices offer an effortless way since they are equipped with computing resources. For instance, Fitbit developed some devices capable of measuring the baseline skin temperature during the night [22]. The individual should only wear their wrist device without requiring additional hardware for data collection.

Heart rate

Heart rate measures the beats per minute of heart activity [23]. A typical heart rate ranges from 60 to 90 BPM. With a 1ºC elevation in body temperature, there is approximately the same amount of an 8.5 BPM increase in heart rate [4, 24]. Traditional methods to measure heart rate include ECG. However, such methods rely on the subject using several electrodes attached to its chest and wired to a central unit that processes the data. Although accurate, such systems might be impractical for daily activity monitoring. Thus, current initiatives explore different strategies from bioelectric sources. Smart bands generally use photoplethysmography (PPG) to measure heart rate. When the heart beats, capillaries expand and contract based on the volume changes in the blood. PPG is a non-invasive optical technique capable of measuring blood volume variations in the capillary structure [25]. The PPG sensor uses a light-emitting diode (LED) that penetrates the skin and travels through the tissue, signaling its intensity to a detector, using reflections. Green LEDs have proved themselves to be more accurate in measuring heart rate due to their penetration intensity.

Heart rate variability

The variation in heart rate is the time interval between two beats in the cardiac cycle, and its decrease may worsen the clinical condition [26]. It varies between people, and a high value represents a more significant resistance to stress, while a low value may indicate disease, stress, depression, or anxiety [27]. Lowered values may provide an early indication that the individual is suffering from infection [4]. As for heart rate, traditional strategies measure HRV through ECG, therefore, suffering from mobility problems. In turn, wearable smart bands rely on the heartbeat measurements they are capable of measuring. By computing the root mean square of successive differences between normal heartbeats (RMSSD), it is possible to determine the HRV using heart rate measurements [28]. Therefore, devices that support heart rate can automatically provide HRV.

Oxygen Saturation

The oxygen level in the blood may decrease as the lung is affected and cannot perform gas exchange properly. SpO2 sensors can detect the amount of oxygen transported by hemoglobin molecules through peripheral blood. In summary, SpO2 is the percentage of oxygenated blood [29]. In individuals with rates below 95%, it is a warning sign and may indicate shortness of breath. Oxygen levels usually stay constant during all daily activities, including exercises and sleeping. Traditional methods to compute SpO2 rely on PPG signals composed of red and infrared light sensors applied to body extremities [29]. The method consists of emitting light signals passing them through the venous blood. Most oximeters available on the market have a clip design composed of two parts: one equipped with sensors to emit light and the other with a receiver. Although non-invasive, their placement can cause some discomfort to the individual since it can interfere with hand activities. Therefore, wristband devices appear as a comfortable alternative. Intelligent wearable devices use red and infrared LEDs that, when aimed against the skin, are reflected in a certain intensity that estimates how much oxygen the blood has. Blood rich in oxygen reflects more red light than infrared light. The opposite happens with poorly oxygenated blood when more infrared light is reflected [30]. Instead of clipping a device in a finger, the individuals can only wear a smart wrist band, and they are good to go.

Enabling technologies

This study aims to bring light upon modern IoHT devices capable of effortlessly monitoring the aforesaid vital signs. This section introduces several smart bands and smartwatches currently available on the market for consumers. To reach them, we searched for articles and manufacturer websites to find which wearable devices can capture the vital signs of interest. Therefore, our methodology includes two different phases. First, we searched for devices on the internet, looking at traditional health-driven brands and news. Then, we selected devices employed in literature searching PubMed (https://pubmed.ncbi.nlm.nih.gov/) and Google Scholar (https://scholar.google.com/) with the following search strings:

- (biomedical OR health AND wearable AND IoHT OR IoT AND “remote health monitoring”);
- (biomedical OR health AND wearable AND COVID-19 AND detection OR monitoring);
- (IoHT OR IoT AND COVID-19 AND detection OR monitoring).

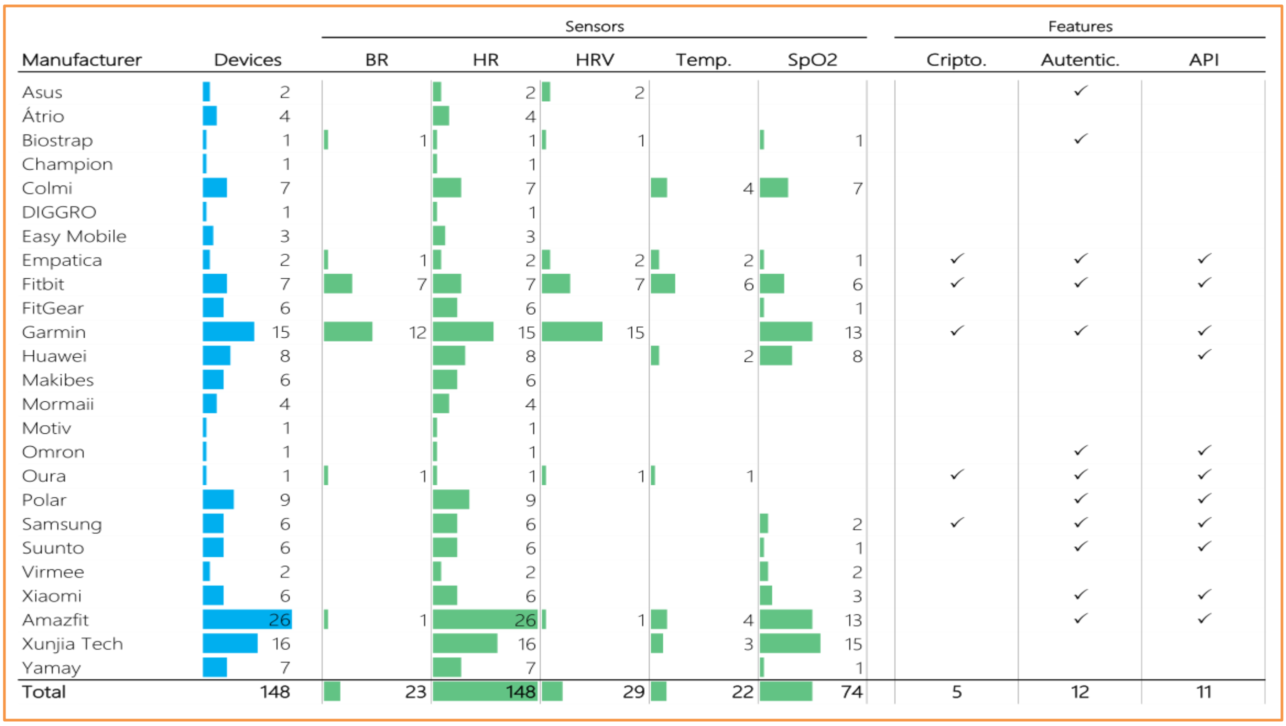
Based on the collection of devices found, we fetched their technical datasheet from their manufacturer when available. We analyzed relevant characteristics of smart wearable devices that can guide their employment on IoHT solutions for COVID-19 and long COVID-19 monitoring. This analysis also includes security aspects, use cases, API and SDK support, and communication protocols. Table 1 lists the 148 resulting devices that we discuss in the following. The first thing the reader can notice is the extensiveness of the table. Currently, smartwatches and smart bands are becoming very popular for personal monitoring. Technology manufacturers offer a wide variety of devices for final customers. They also provide mobile applications for Android and IOS, enabling users to visualize their data and set alerts and alarms based on them. In some cases, manufacturers also provide API features where users can access their data for its purpose. That enables the development of applications using users’ data gathered from their devices. This feature relies upon the possibility of using such devices for vital signs monitoring to control the evolution of COVID-19 in a population. Because of data sensitiveness, accessing data through APIs should provide authentication and cryptography methods, which most API-enabled devices offer. Summarizing the tables' devices, 58.8% of them offer support to data extraction through an API. Although considerable, it is important to note that it depends on the manufacturer offering this feature. Thus, as there are several devices from the same manufacturer, all of them can benefit from the offered API. To clear things up, only 11 from 25 (44%) manufacturers present in the table provide an API. Providing an API is crucial for initiatives to build solutions upon wearable devices. The lack of this feature opens gaps future manufacturers are required to close. Fitbit and Garmin are the friendliest companies, providing robust API documentation and SDK support from a developer’s viewpoint. SDK helps capture the data and use them on Web-based or smartphone applications. With HTML5 (HyperText Markup Language 5) and asynchronous messages, notifications inform the patient or institutions about actual problems or those that are being predicted. On this aspect, the most significant difference between Fitbit and Garmin's devices is the programming language options. Fitbit has Javascript support, which supports SVG (Scalable Vector Graphics) and CSS (Cascading Style Sheets) plugins, while Garmin presents an object-oriented language (Monkey C). Worth noting that Xiaomi devices do not provide any native API for data capture. Nevertheless, with the integration of Google Fit, this becomes available through a REST (Representational State Transfer) API and Android Studio SDK. Looking closely at the devices in the table, we can highlight the following points: (i) just a few devices collect all five parameters; (ii) heart rate is the most popular vital sign; (iii) Bluetooth is the standard communication protocol, and (iv) direct connection to the internet is available on only a few devices. First, a device that collects as many as possible vital signs parameters permits the user to wear fewer devices and, therefore, they are likely to use it in a daily-basis manner. However, the table shows that only seven (4.7%) devices have a complete set of sensors. Fitbit manufactures six of them, while Empatica manufactures the other one. Corroborating with the literature [10, 11], the leading devices in use to monitor COVID-19 are from Fitbit. Fitbit offers end-user devices that combine design and functions to provide complete solutions. On the other hand, Empatica focuses on medical applications providing its device to patients. The full sensor devices they provide can be considered way-to-go strategies for future technology on patient monitoring. Again, patients are more prone to use a single, smart band rather than several devices in different body parts. Second, the table shows that all devices provide heart rate parameters. Heart rate is the opening door for health trackers for final customers. The first versions of each device in this area started tracking this parameter. Besides being a well-known vital sign, the main reason for that is the technological evolution on red and infrared sensors, which allows equipping them to small devices. Further, manufacturers focus on making a profit, and providing this sensor can easily catch end-user attention. Third, looking at communication protocols, Bluetooth (https://www.bluetooth.com/) appears to be the leading technology. Bluetooth is a wireless technology for short-range communication widely employed in portable devices [31]. It is managed by the Bluetooth Special Interest Group (SIG), and it is currently in version 5.3. In its version 4.0, from 2009, it introduced Bluetooth Low Energy (BLE), intended to reduce power consumption. This important point makes BLE very popular since battery life is a crucial capability manufacturer seek to improve. Wearable smartwatches and smart bands are primarily designed to communicate with smartphones, making Bluetooth an obvious choice since all current smartphones support it. Finally, although most devices intend to communicate with the manufacturer’s mobile application, some devices also have Internet capabilities. Garmin, Huawei, Samsung, and Amazfit provide a total of 15 devices equipped with WiFi and/or LTE (Long-Term Evolution) technology. That makes them totally independent from smartphones to provide features beyond vital signs monitoring. However, data extraction follows the same pattern: a mobile application collects and processes the data. Even though not common, such capability could enable such devices to directly access the user data. Currently, most devices are smartphones- dependent and future directions can consider employing a data server directly on the device. Table 1 presents a massive amount of information regarding many sensors and manufacturers. That might turn it confusing for the reader that aims at looking for specific manufacturers based on the options they offer. To facilitate this process, we present in Figure 2 a summary of each manufacturer from Table 1. The figure shows the number of devices by the manufacturer and the number of devices that implement each sensor. In addition, it also presents the features the manufacturers provide if they implement them for at least one device. Through the figure, the reader can select a particular manufacturer and then look for its devices in Table 1. For instance, the figure shows that Garmin provides more devices for most sensors. Moreover, it also shows that Fitbit has several devices for each sensor.

Table 1: List of sensor devices employed on monitoring the following health parameters.

Device	**Model**	**Vital Signs**					**Security**		**API**	**Communication**
		Respiratory Rate	**Heart Rate**	**Heart Rate Variability**	**Bory Temperature**	**Oxygen Saturation**	**Cryptography**	**Authentication**		
Asus VivoWatch BP	Asus		P	P				P		Bluetooth 4.2
Asus VivoWatch SP	Asus		P	P				P		Bluetooth 4.2
ROMA	Átiro		P							Bluetooth 5.0
VIENA	Átrio		P							Bluetooth 5.0
LONDRES	Átrio		P							Bluetooth 5.0
PARIS	Átrio		P							Bluetooth 5.0
EVO Wristband	Biostrap	P	P	P		P		P		Bluetooth
Champion Smartwatch	Champion		P							Bluetooth 4.0
Land 2	Colmi		P		P	P				Bluetooth
Land 2S	Colmi		P		P	P				Bluetooth
Sky 1	Colmi		P			P				Bluetooth
Sky 7	Colmi		P			P				Bluetooth
Sky 8	Colmi		P			P				Bluetooth
P8	Colmi		P		P	P				Bluetooth
V23 Pro	Colmi		P		P	P				Bluetooth
DIGGRO N88	DIGGRO		P							Bluetooth 4.0
Smart Bracelet HR 2	Easy Mobile		P							BLE 4.2
Style Fit HR	Easy Mobile		P							BLE 4.2
Ultra Fit BP	Easy Mobile		P							BLE 4.2
E4 wristband	Empatica		P	P	P		P	P	P	USB 2.0 e BLE
Embrace PLUS	Empatica	P	P	P	P	P	P	P	P	USB 2.0 e BLE
Fitbit Sense	Fitbit	P	P	P	P	P	P	P	P	WiFi, BLE, NFC
Fitbit Versa 2	Fitbit	P	P	P	P	P	P	P	P	WiFi, BLE, NFC
Fitbit Versa 3	Fitbit	P	P	P	P	P	P	P	P	WiFi, BLE, NFC
Fitbit Charge 5	Fitbit	P	P	P	P	P	P	P	P	BLE, NFC
Fitbit Luxe	Fitbit	P	P	P	P	P	P	P	P	BLE
Fitbit Inspire 2	Fitbit	P	P	P			P	P	P	BLE
Fitbit Ionic	Fitbit	P	P	P	P	P	P	P	P	WiFi, BLE, NFC
FitGear Force Effect	FitGear		P							Bluetooth 4.0
FitGear W34S Plus	FitGear		P							Bluetooth 4.0
FitGear Fusion	FitGear		P							Bluetooth 4.0
Fitgear Intense	FitGear		P							Bluetooth 4.0
FitGear Skill Pro	FitGear		P							Bluetooth 4.0
FitGear D13	FitGear		P			P				Bluetooth 4.0
Garmin Vivoactive 4	Garmin	P	P	P		P	P	P	P	WiFi, Bluetooth, ANT+
Garmin Venu 2	Garmin	P	P	P		P	P	P	P	WiFi, Bluetooth, ANT+
Garmin Venu Sq	Garmin	P	P	P		P	P	P	P	Bluetooth, ANT+
Garmin Forerunner 945	Garmin	P	P	P		P	P	P	P	WiFi, Bluetooth, ANT+
Garmin Forerunner 945 LTE	Garmin	P	P	P		P	P	P	P	WiFi, Bluetooth, ANT+, LTE
Garmin Forerunner 55	Garmin	P	P	P			P	P	P	Bluetooth, ANT+

Garmin Forerunner 745	Garmin	P	P	P		P	P	P	P	WiFi, Bluetooth, ANT+
Garmin Forerunner 245	Garmin		P	P		P	P	P	P	Bluetooth, ANT+
Garmin Instinct	Garmin		P	P			P	P	P	Bluetooth, ANT+
Garmin Instinct Solar	Garmin		P	P		P	P	P	P	Bluetooth, ANT+
Garmin fênix 6	Garmin	P	P	P		P	P	P	P	Bluetooth, ANT+
Garmin fênix 6 Pro	Garmin	P	P	P		P	P	P	P	Wifi, Bluetooth, ANT+
Garmin fênix 6S	Garmin	P	P	P		P	P	P	P	Bluetooth, ANT+
Garmin fênix 6S Pro	Garmin	P	P	P		P	P	P	P	Wifi, Bluetooth, ANT+
Garmin fênix 6X Pro	Garmin	P	P	P		P	P	P	P	Wifi, Bluetooth, ANT+
Huawei Watch GT 3	Huawei		P			P			P	Bluetooth
Huawei Watch 3	Huawei		P		P	P			P	WiFi, Bluetooth 5.2, BLE, NFC, LTE
Huawei Watch 3 Pro	Huawei		P		P	P			P	WiFi, Bluetooth 5.2, BLE, NFC, LTE
Huawei Watch GT 2 Pro	Huawei		P			P			P	Bluetooth
Huawei Watch Fit	Huawei		P			P			P	Bluetooth 5.0, BLE
Huawei Band 6	Huawei		P			P			P	Bluetooth 5.0, BLE
Huawei Band 4	Huawei		P			P			P	Bluetooth 4.2
Huawei Band 4 Pro	Huawei		P			P			P	Bluetooth 4.2
HR5	Makibes		P							Bluetooth 4.0
HR3	Makibes		P							Bluetooth 4.0
BR1	Makibes		P							Bluetooth 4.0
G07	Makibes		P							Bluetooth 4.0
G06	Makibes		P							Bluetooth 4.2
G03	Makibes		P							Bluetooth 4.2
Mormaii Evolution	Mormaii		P							Bluetooth
Mormaii Life	Mormaii		P							Bluetooth
Mormaii Smart	Mormaii		P							Bluetooth
Mormaii Fitsport	Mormaii		P							Bluetooth
Motiv Ring	Motiv		P							Bluetooth
Heart Guide	Omron		P					P	P	BLE
Oura Ring	Oura	P	P	P	P		P	P	P	BLE
Grit X Pro	Polar		P					P	P	BLE, USB
M430	Polar		P					P	P	BLE, USB
Ignite	Polar		P					P	P	BLE, USB
Ignite 2	Polar		P					P	P	BLE, USB
Vantage M	Polar		P					P	P	BLE, USB
Vantage M2	Polar		P					P	P	BLE, USB
Vantage V	Polar		P					P	P	BLE, USB
Vantage V2	Polar		P					P	P	BLE, USB
Polar Unite	Polar		P					P	P	BLE, USB
Galaxy Watch 4	Samsung		P			P	P	P	P	WiFi, BLE, NFC, LTE
Galaxy Watch 3	Samsung		P			P	P	P	P	WiFi, BLE, NFC, LTE
Galaxy Watch Active2	Samsung		P				P	P	P	WiFi, NFC, LTE, Bluetooth 5.0
Galaxy Watch Active	Samsung		P				P	P	P	WiFi, NFC, Bluetooth 4.2
Galaxy Fit2	Samsung		P				P	P	P	Bluetooth 5.1
Galaxy Fit	Samsung		P				P	P	P	BLE 5.0
Suunto 9 Peak	Suunto		P			P		P	P	BLE
Suunto 9	Suunto		P					P	P	BLE
Suunto 7	Suunto		P					P	P	BLE, NFC
Suunto 5	Suunto		P					P	P	BLE
Suunto 3	Suunto		P					P	P	BLE
Ambit3	Suunto		P					P	P	BLE, USB
Gearfly VG3	Virmee		P			P				BLE 5.0
Tempo VT3	Virmee		P			P				BLE 5.0
Mi Watch	Xiaomi		P			P		P	P	BLE 5.0
Mi Watch Lite	Xiaomi		P					P	P	BLE 5.0
Redmi Watch 2 Lite	Xiaomi		P			P		P	P	BLE 5.0
Mi Smart Band 6	Xiaomi		P			P		P	P	BLE 5.0, NFC
Mi Smart Band 5	Xiaomi		P					P	P	BLE 5.0
Mi Smart Band 4C	Xiaomi		P					P	P	BLE 5.0
Band 5	Amazfit		P			P		P	P	Bluetooth 5.0 BLE
Bip	Amazfit		P					P	P	Bluetooth 4.0 BLE
Bip Lite	Amazfit		P					P	P	Bluetooth 4.1 BLE
Bip S	Amazfit		P					P	P	BLE 5.0
Bip S Lite	Amazfit		P					P	P	BLE 5.0
Bip U	Amazfit		P			P		P	P	Bluetooth 5.0 BLE
GTR	Amazfit		P					P	P	Bluetooth 5.1 BLE
GTR 2	Amazfit		P			P		P	P	Bluetooth 5.0, WiFi
GTR 2e	Amazfit		P		P	P		P	P	Bluetooth 5.0 BLE

GTR 3	Amazfit		P			P		P	P	Bluetooth 5.1 BLE
GTR 3 Pro	Amazfit	P	P		P	P		P	P	Bluetooth 5.0, WiFi
GTS	Amazfit		P					P	P	Bluetooth 5.0 BLE
GTS 2	Amazfit		P			P		P	P	Bluetooth 5.0, WiFi
GTS 2e	Amazfit		P		P	P		P	P	Bluetooth 5.0 BLE
GTS 2 Mini	Amazfit		P			P		P	P	Bluetooth
GTS 3	Amazfit		P		P	P		P	P	Bluetooth 5.0 BLE
Neo	Amazfit		P					P	P	Bluetooth 5.0 BLE
Nexo	Amazfit		P					P	P	Bluetooth 4.2, BLE, WiFi
Stratos	Amazfit		P					P	P	Bluetooth 4.0, WiFi
Stratos 3	Amazfit		P					P	P	Bluetooth 4.2, BLE 5.0, WiFi
Stratos +	Amazfit		P					P	P	Bluetooth 4.0, WiFi
TRex	Amazfit		P			P		P	P	BLE 5.0
TRex Pro	Amazfit		P	P		P		P	P	Bluetooth 5.0 BLE
Verge	Amazfit		P					P	P	Bluetooth 4.2, BLE, WiFi
Verge Lite	Amazfit		P					P	P	Bluetooth 5.0 BLE
X	Amazfit		P			P		P	P	Bluetooth 5.0 BLE
I12 Smartwatch	Xunjia Tech		P			P				Bluetooth 5.2
HW12 Smartwatch	Xunjia Tech		P		P	P				Bluetooth 5.2
F20 Smartwatch	Xunjia Tech		P			P				BLE 5.0
X7 Smartwatch	Xunjia Tech		P			P				Bluetooth 4.2 + 5.0
W26 Smartwatch	Xunjia Tech		P		P	P				Bluetooth
K9 Smartwatch	Xunjia Tech		P			P				Bluetooth 4.0
P40 Smartwatch	Xunjia Tech		P			P				Bluetooth 4.0 BLE
W34 Smartwatch	Xunjia Tech		P							Bluetooth 5.0
P80 Smartwatch	Xunjia Tech		P			P				Bluetooth 4.0
W20 Smartwatch	Xunjia Tech		P			P				Bluetooth
E66 Smart Bracelet	Xunjia Tech		P		P	P				BLE 4.0
M5 Smart Bracelet	Xunjia Tech		P			P				Bluetooth 5.0
M4 Smart Bracelet	Xunjia Tech		P			P				BLE 4.0
M3 Smart Bracelet	Xunjia Tech		P			P				BLE 4.0
S5 Smart Bracelet	Xunjia Tech		P			P				Bluetooth 4.0
C1 Smart Bracelet	Xunjia Tech		P			P				Bluetooth 4.0
SW020 Smartwatch	Yamay		P							Bluetooth
SW021 Smartwatch	Yamay		P							Bluetooth
SW023 Smartwatch	Yamay		P			P				Bluetooth
SW350 Fitness Tracker	Yamay		P							Bluetooth 4.0
SW351 Fitness Tracker	Yamay		P							Bluetooth 4.0
SW352 Fitness Tracker	Yamay		P							Bluetooth 4.0
SW333 Fitness Tracker	Yamay		P							Bluetooth 4.0



		Sensors					Features		
Manufacturer	Devices	BR	HR	HRV	Temp.	SpO2	Cripto.	Autentic.	API
Asus	2		2	2				✓	
Átrio	4		4						
Biostrap	1	1	1	1		1		✓	
Champion	1		1						
Colmi	7		7		4	7			
DIGGRO	1		1						
Easy Mobile	3		3						
Empatica	2	1	2	2	2	1	✓	✓	✓
Fitbit	7	7	7	7	6	6	✓	✓	✓
FitGear	6		6			1			
Garmin	15	12	15	15		13	✓	✓	✓
Huawei	8		8		2	8			✓
Makibes	6		6						
Mormaii	4		4						
Motiv	1		1						
Omron	1		1					✓	✓
Oura	1	1	1	1	1		✓	✓	✓
Polar	9		9					✓	✓
Samsung	6		6			2	✓	✓	✓
Suunto	6		6			1		✓	✓
Virmee	2		2			2			
Xiaomi	6		6			3		✓	✓
Amazfit	26	1	26	1	4	13		✓	✓
Xunjia Tech	16		16		3	15			
Yamay	7		7			1			
Total	148	23	148	29	22	74	5	12	11

Figure 2: Infographic summarizing all manufactures by the number of devices, sensors covered, and featuresthey provide.

Challenges and future directions

Given the wide list of devices and their capabilities presented in the former section, it is valuable to understand their deficiencies and what they can do. Therefore, this section first presents a discussion on the vital signs' capabilities of the presented devices. Then, we introduce future directions on smart cities and intelligent solutions for COVID-19 monitoring.

Analyzing the current IoT devices for vital signs collection

The several available devices allow developing systems and platforms to track peoples' health in real-time. Although the idea seems interesting, the manufacturers impose differences between what can be obtained directly with built-in sensors and what can be obtained from their mobile application. Thus, if a developer plans to capture data from a smart band to his/her smartphone app, we must understand that they could be different from those available in the manufacture's application. Also, we observed that only seven of the devices could monitor the five vital sign parameters this article targets. For instance, Fitbit has six devices that monitor all vital signs: Fitbit Sense, Fitbit Versa 2, Fitbit Versa 3, Fitbit Charge 5, Fitbit Luxe, and Fitbit Ionic. In turn, Empatica has a device that also has this comprehensive cover. The other devices are deficient in this regard, as they only cover four or fewer vital signs. While all devices have heart rate monitoring, 74 (50%) have SpO2, 29 (19.6%) have HRV monitoring, only 22 (14.9%) have temperature sensors, and only 23 (15.5%) have respiratory rate monitoring. The devices' lack of monitoring of temperature and HRV is shown as a limitation, considering that they are vital signs with crucial evidence to aid in the early detection of symptoms of COVID-19. Not having all sensors in a single device requires more than one device, which might become impractical. Our findings focused on two critical aspects of developing IoT solutions: the support of an open API; and the assurance of private user data security. In both aspects, the companies discovered specific negligence when providing tools and documentation for the correct use, transport, and manipulation of data. Excluding the leading tech companies like Fitbit, Garmin, and Samsung, most devices do not provide any practical way of obtaining data. They only allow data visualization through proprietary mobile applications. Only these prominent companies described their security techniques that provide the secure exchange of personal information, mainly with OAUTH2 and hash cryptography. Privacy is not protected because each company collects and handles personal data with the user's consent, which is common nowadays. The lack of sensors imposes challenges requiring the combination of two or more parameters in diagnosis. In turn, smart wearable devices in health applications are relatively new. Manufacturers still focus on fitness, personal care, and sports. Some of these devices have already been used in healthcare, authorized by the owners. However, their use is only in scientific studies, not having a health-focused device for disease monitoring with proven accurate vital signs detection. With previously tested and approved applications, studies can evaluate the accuracy of these devices through their API and SDK support. The confinement needed to fight the COVID-19 pandemic has denied the population to keep a routine of medical appointments, bringing social and economic troubles. In doing so, we highlight the growing need for remote health surveillance, and telemedicine, besides investments in smart cities and tech hospitals.

Towards providing scalable and intelligent solution

Employing several sensor devices to monitor the health parameter of people daily is crucial to track and monitor the spread of new diseases. With that in mind, we envisage a broad monitoring infrastructure for smart cities as an opportunity to improve several aspects of public health. To illustrate that, we present in Figure 3 a smart city architecture focusing on mobile health and vital signs collection. People can use wearable devices to transmit their health parameters to the public health infrastructure in real-time, not limited to a particular location. Through the employment of Fog and Cloud Computing, it is possible to provide several health services to patients in a new paradigm in which the public health system can deliver intelligent services on-demand in an asynchronous prediction-wise manner. Such services are possible through the employment of inferential statistics and machine learning methods to enable: (i) event prediction (Autoregressive Integrated Moving Average - ARIMA, Random Forest, Neural Networks, Linear and Logistic Regression); (ii) cause-effect correlations (confusion matrices, Pearson's coefficient, cosine's rule); (iii) data classification (Support Vector Machine, k-Nearest Neighbours); and (iv) pattern recognition (K-means clustering, Neural Networks). For instance, a health surveillance system can predict health disorders of a person wearing health sensors. Thus, the system can assist patients before realizing they need it. In a more practical example, a hospital can send an ambulance directly to a patient's house once they realize that the patient is close to a critical health crisis. This example depicts how such infrastructure can revolutionize how health services are provided to patients. In addition, through the prism of a pandemic situation, the public health system can track the spread of diseases by correlating patient data. Therefore, it would be possible to quickly identify regions with higher risk and trigger measures to contain the spread of diseases. In the same way, by combining vital signs and GPS (Global Positioning System) data, we can either analyze the efficiency of lockdown policies or generate cost-efficient plans to reopen cities in a secure and timely way.

Given the heterogeneity of devices and sensors at the network's edge, extracting, and transmitting their data is challenging. Several factors should be considered when deploying monitoring devices for remote patients: data regulations, user authentication, data privacy, devices API availability, data extraction mechanism, data processing middleware, and data transmission (including the protocol, use of brokers, and data compression). Currently, to the best of our knowledge, there are no application and platform standards that define how to achieve data collection and transmission for health parameters at the edge. Therefore, we envisage an Edge Controller placed near the patient who can collect, process, and transmit data to the Fog infrastructure. Figure 4 presents the Edge Controller architecture and possible deployments at the patient's site. At the left, Figure 4a introduces several components and how they interact to process data from sensors. In turn, Figure 4b demonstrates possible deployments.

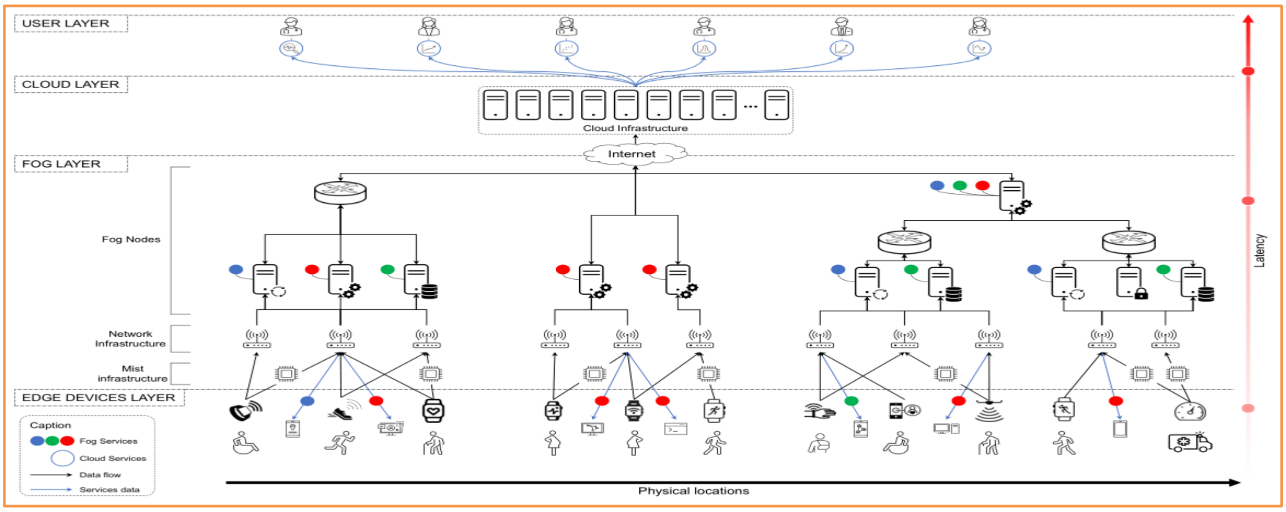


Figure 3: Smart city architecture with a focus on monitoring patients' health parameters. People wear sensors that transmit health parameters to a Fog-Cloud infrastructure that provides health services.

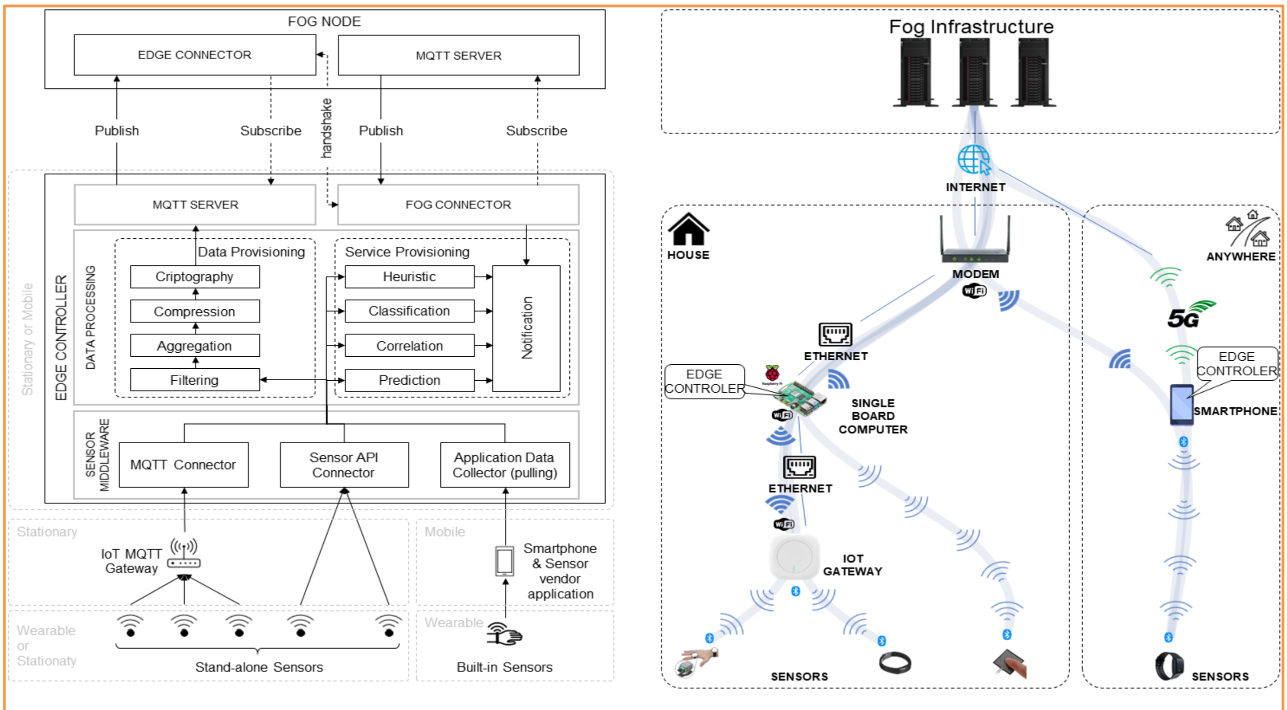
Health services in the edge site or the Fog node can be assisted with vertical elasticity and Serverless computing. The first is pertinent to resize virtual resource capabilities (such as vCPU or vMem) between two or more services depending on the incoming requests on each one, for example. The Serverless platform is responsible for spawning multiple instances of a given function according to the number of requests to achieve the desired scalability. Cost is measured in minutes or hours but in the number of managed containers and each specific time. Containers are usually employed to sandbox functions. In addition, we envisage the use in the future of Unikernel and WebAssembly technologies. Unikernel relies on a hypervisor and boots incredibly fast, in addition to running everything in a single address space (it does not have the overhead of switching between kernel and userspace). WebAssembly (sometimes abbreviated Wasm), in its turn, is an open standard that defines a portable binary-code format for executable programs and a corresponding textual assembly language, as well as interfaces for facilitating interactions between such programs and their host environment. In addition to cloud elasticity, we envisage data compression on transmitting data from the edge to the Fog node. Here we are not talking about the typical compression task but about communicating pertinent data when necessary. Data are sent based on periodicity needed for a particular vital sign, considering the needs of each citizen. Another keyword when collecting vital signs in a broader vision is privacy. We plan to incorporate Federated Learning and homomorphic cryptography concepts in the smart city solution to support it. With Federated Learning, data stays with users, and the user trains the machine learning models; then, the gradients from the training are aggregated by a central server to improve the global model. Expanding the topic to the context of intelligent hospitals, Federated Learning by itself does not guarantee security to the services. Homomorphic cryptography is helpful to combine through arithmetic operations data from the users in the Federated Learning process. Also, using the addition operation, this new kind of cryptography can generate insights over the data without deciphering them. For instance, it is possible to observe the number of people with fever or a particular disease in a city district.

Figure 4b illustrates the deployment of an Edge Controller by showing three different data flows. The Edge Controller could run in a single board computer (SBC) connected to the local network at the patient's home, like a Raspberry Pi. Data from sensors can be extracted by the Edge Controller directly from sensors using Bluetooth or through the IoT Gateway. Also, an Edge Controller could run at the patient’s smartphone as an application acquiring data from the sensor’s vendor application API. Here, data is extracted by the vendor application and made available locally. Employing SBC or a smartphone depends on the use case. An SBC reaches the internet through the Internet Service Provider (ISP) modem and can interact with as many sensors as available at the patient’s house. In turn, the smartphone strategy brings the advantage of constant monitoring no matter where the patient is. Therefore, the patient can have constant feedback from its local context and, when a connection with the internet is available, from the Fog context. The only drawback is the limitation of sensors and battery consumption.

Final Remarks

This article presented a broader vision about the most important vital signs in the scope of the COVID-19 pandemic, presenting details of sensing technologies and insights about monitoring a whole population. The deaths attributed to the pandemic are nowadays decreasing; however, it is essential to understand the potential damage of the virus scientifically for the rest of the patients’ life. Thus, our study gains a vaster audience since vital signs monitoring is advantageous for proactively analyzing health conditions. Moreover, the price of the sensors has been decreasing as people are getting more and more connected, allowing health maintenance and surveillance easier.

Currently, we are witnessing a turning point for healthcare solutions adopting IoT technologies. Several commercial systems and initiatives are available to bring health monitoring close to the final users. Medical information of patients is sensitive, and regulations must be followed when providing it to them. It is common to see initiatives focusing on developing devices under Food and Drug Administration (FDA) regulations to turn them more reliable. Although important, such technologies should not be the only source of information. They can provide guidance information for patients when correctly interpreted by medical assistance. Therefore, patients using IoT technology should still find professional medical assistance. Analyzing the current IoT devices, the lack of transparency on the development and security subjects became evident on the destructive aspect. Most manufacturers do not provide comprehensive documentation or the necessary tools for developing and revising applications. In conclusion, this study aims to help the development of architectures and solutions to turn the IoHT more accessible and reliable. This article contributes not only to ordinary citizens but also to research projects related to COVID-19. Additionally, the applications and directions this study gives are pertinent to government agencies in leading, controlling, and monitoring virus transmission. Thus, we intend to develop policies for the creation of innovative and safer cities.



(a) Edge Controller architecture and data flow. (b) Local deployment at the Edge.

Figure 4: Edge architecture and deployment proposal.

Abbreviation

NAPI: Application Programming Interface; ARIMA: Autoregressive Integrated Moving Average; BLE: Bluetooth Low Energy; BPM: Beats Per Minute; BRPM: Breathings Per Minute; CNT: Carbon Nanotube; COVID-19: Coronavirus Disease; CSS: Cascading Style Sheets; ECG: electrocardiography; FDA: Food and Drug Administration; GPS: Global Positioning System; HRV: Heart Rate Variability; HTML5: HyperText Markup Language 5; IoHT: Internet of Health Things; IoT: Internet of Things; ISP: Internet Service Provider; K: Kelvin; LED: light-emitting diode; LTE: Long-Term Evolution; ºC: Celcius; ºF: Farenhight; PPG: photoplethysmography; REST: Representational State Transfer; RMSSD: root mean square of successive differences between normal heartbeats; SARS-CoV-2: severe acute respiratory syndrome coronavirus 2; SBC: Single Board Computer; SDK: Software Development Kit; SIG: Special Interest Group; SpO2: peripheral oxygen Saturation (SpO2) SVG: Scalable Vector Graphics

Declaration

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Availability of data and materials

Data will be available by emailing vfrodrigues@unisinos.br

Authors' contributions

All authors equally contributed to the concept, design, literature search, data analysis, and data acquisition, manuscript writing, editing, and reviewing. All authors read and confirm the final draft.

Ethics approval and consent to participate

We conducted the research following the Declaration of Helsinki. However, the review articles need no ethics committee approval. All images (in Figure 1,2,3,4) presented in the current study belong to the author (S). The Journal disclaims all responsibility, and the author (s) are responsible for the use of all images (Figure 1,2,3,4) in the article.

Consent for publication

Not applicable

Competing interest

The authors declare that they have no competing interest.

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