A Low-Cost Control Occupancy Solution Using a Time-of-Flight Ranging Sensor Laser

Enric Bartrés Jurado[1], Sergio Trilles Oliver[1,2], Antoni Perez Navarro[1,3] and Joaquín Torres-Sospedra[4]

[1] *Faculty of Computer Sciences, Multimedia and Telecommunication, Universitat Oberta de Catalunya, Barcelona, Spain.*

[2] *Institute of New Imaging Technologies, Universitat Jaume I, Castellón, Spain.*

[3] *Internet Interdisciplinary Institute (IN3), Universitat Oberta de Catalunya, Castelldefels, Spain.*

[4] *UBIK Geospatial Solutions S.L., Castellón, Spain.*

Abstract

The pandemic situation has driven to several measures to prevent the spread of COVID-19. One of these measures is social distance and, as a consequence, limitation of capacity of indoor closed spaces. This makes necessary the deployment of systems that help to control occupancy of spaces. This work proposes a low-cost system to control access to an indoor closed space with a single door. The system is based in a two laser Time-of-Flight sensors *VL53L0X* over a *HiLetgo UNO R3D1R32 ESP32* micro-controller. The system counts the occupancy of the room and share it with a database and a dashboard, using Node-RED. The tested prototype shows a 86.6% reliability that increases to a 100% reliability when users are informed to enter or exit one by one. The main contributions of this work are: to control capacity of one-entrance indoor closed space with a low cost open system; and to record occupancy of the room in order to analyse it behaviour with time.

Keywords

Occupancy control, Internet of Things, open-hardware, Sensor systems

1. Introduction

Among the main measures applied to fight against COVID-19 is the use of mask, the closure of public spaces (children's parks, sports venues, libraries, ...), restrictions on mobility (border control, perimeter restrictions,...) or occupancy restrictions [1]. Some of these measures are due to maintain social distancing since it has been one of the more successful measures to stop the pandemic [2].

Occupancy restriction in indoor spaces allows to maintain social distancing and also helps to keep those spaces well ventilated. To control that capacity of spaces is not exceeded, several techniques have been developed in a short time [3]. This rapid adaptation has been possible thanks to the high degree of advancement in the Internet of Things (IoT) paradigm and the availability of sensor devices [4, 5]. This scenario has facilitated the deployment of devices capable of monitoring and acting remotely to control different established restrictions.

Regarding occupancy control, several solutions had been applied to detect occupancy in buildings to reduce energy costs [6]. These technological solutions are based on RGB cameras

---

IPIN 2021 WiP Proceedings, November 29 – December 2, 2021, Lloret de Mar, Spain

[7], break-beam sensors, Ultrasonic sensors [8], temperature sensors, light sensors, WiFi sensing [9] or ultra-wideband (UWB). All these technologies are detailed and compared deeply in Section 2.

In this work, we propose a solution to control occupancy in a closed space (*room*) with a single entrance and exit. The platform proposed is a low-cost system based on open-hardware and open software components, with a management control panel. The solution presented is not intrusive for users and allow to perform real-time control of room capacity.

The system proposed has two parts: a hardware device, that is based on *HiLetgo UNO R3 D1 R32 ESP32* and the Time-of-Flight (ToF) ranging laser distance sensors called *VL53L0X*; a back-end platform, developed in Node-RED, that obtains the number of people in the room from the hardware and shows the information in a comprehensive way. Tests were performed in a hospital room located in Hospital de Mataró (Catalunya, Spain) is used as an experimentation scenario.

In summary, the main contributions of this work are: (1) to develop a prototype capable of counting the people entering and leaving an enclosed space, thus allowing the control of capacity automatically; (2) propose a generic solution without any additional element for people; (3) define a low-cost solution using open hardware and open software; and (4) record and visualise the data of the occupancy for future research studies.

2. Background

Occupancy control has been a topic of interest for different reasons: security, since it allows to control that the number of people in a space that not exceed capacity; traceability since it allows to know occupancy levels and thus making informed decisions; and finally, satisfying laws regarding regulate occupancy control systems, like law 11/2009 [10] of the Government of Catalonia.

The most common tools for occupancy control are: (1) mechanical, like a clicker counter that counts $+1$ or -1 every time a human counter presses a button when a person enters or leaves the closed location, or the turnstiles; (2) electronic devices that automatically controls the number of people that enters or leaves a closed location, based on sensors, cameras or wireless signals; and (3) a reader that counts people reading single-person identifiers, such as bracelets.

In the mechanical sensors category, turnstiles allow for counting without human intervention, and are very common in sports centres or theme parks [11]. However, they are an invasive system and with a very high cost. A recent technology is the pressure mats [12]. This device allows identifying the number of people going through it thanks to a series of pressure sensors that incorporates the same carpet. This technology is quite recent and its cost is very high compared to other technologies.

Within the second category, there are many solutions and types of sensors that can detect people. These are divided into active, passive and mixed sensors [13]. There are several types of active sensors depending on the type of signals. The sensor sends a signal that must bounce on a surface at a known distance, if something interferes with the signal the sensor detects a change in the return time of the signal. The most commonly used signals are microwaves and ultrasounds [14]. In the same category, there are also reflective sensors, which use beams

Table 1
Different technologies to control occupancy in a room

Technology	Feature	Cost(€, sensors only)	Privacy	Scalability	Deployment
Ultrasonic/ Microwaves sensors	Counting	<10	High	Moderate	Moderate
Break Beam sensors	Counting	<10	High	Moderate	Moderate
PIR sensors	Presence	<10	High	Moderate	Moderate
Turnstiles	Counting	< 20.000	High	Low	Difficult
Pressure mats	Counting	High, depending the area to cover	High	Low	Difficult
RGB cameras	Counting	<100	Low	Moderate	Moderate
Thermal cameras	Counting	<80	Moderate	Moderate	Moderate
RFID	Counting	< 10 without tags/cards	Low	Moderate	Moderate
WiFi signals	Counting	<100	Low	High	Easy
Our (ToF sensors)	Counting	<50	High	High	Moderate

of light with an emitting device and a receiver, if this beam of light is crossed by an object, a person is detected [15].

Passive sensors are the most common in domestic security systems. These systems, also called Passive InfraRed (PIR), detect changes in movement or heat through infrared [8, 16]. These sensors are called passive because they do not emit radiation, but receive them. They are composed of an electronic component designed to detect changes in the infrared radiation received. They generally incorporate a transistor that amplifies the electrical signal generated when this variation in radiation received occurs.

RGB or thermal cameras are intended to count the number of people passing through a given place using the corresponding software [17]. Unlike thermal cameras, RGB cameras can be affected by lighting conditions. The main disadvantage for both types is the cost.

WiFi signals have also been used to detect presence. The Received Signal Strength Indicator (RSSI) values generated by the WiFI signals have been used to count the number of people walking through the specific area [6, 18]. Although this approach is not invasive, the user must have a device that generates WiFi signals.

Finally, in the third category, Radio Frequency IDentification (RFID) readers are a system that uses tag or card devices [19]. This system could be used to count people and also identify them, but an RFID tag or card should be provided to all people who need to access it. Thus, this is a system that is more used to count objects with a tag, than people.

Table 1 summarises each technology applied in the field of occupancy control. It shows Technology; Feature, if counts people or detects their presence; Cost; Privacy, where Low means that is easy to know who a single person is, and High is that it is not possible to identify people; Scalability, where Low means that is difficult to increase the number of persons counted; and Deployment, where Easy means that the effort to deploy the system is low. This work focuses on devices in the second category, i.e, electronic devices that automatically control the number of people that enters or leaves a closed location. In the next section, the system proposed will be shown.

3. Method

This section focuses in the design of the proposed solution. Figure 1 shows a general overview with all the elements of the system. The system is based on two main parts: the IoT-physical and the Cloud/Clients cyber.

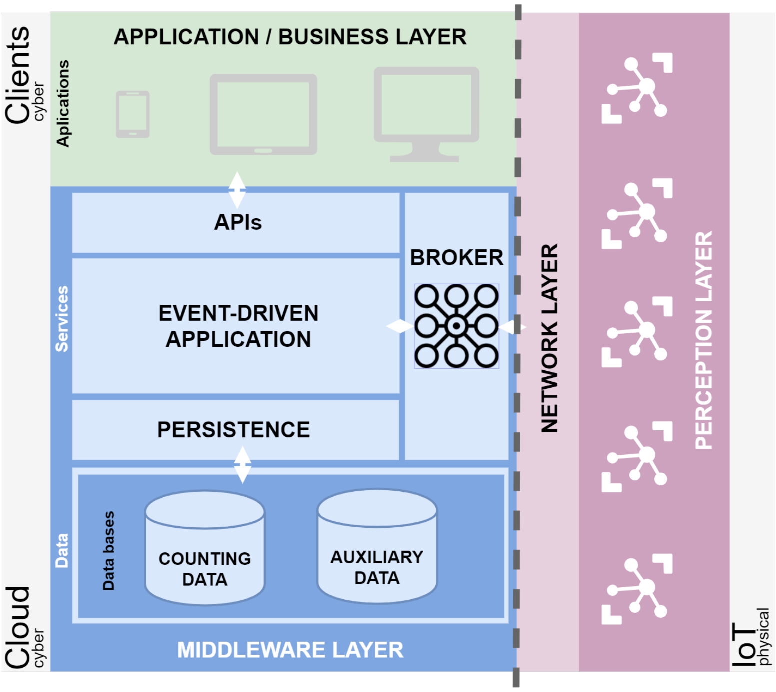


Figure 1: General overview

The Physical scope, on the right side of the dashed line (Figure 1), represents IoT devices from the hardware perspective. Two layers are included in this part: network and perception layers. These two layers cover the IoT devices and, depending on the capabilities of each device, how they can connect to count persons.

Moving to the left part of the figure, for the Cyber scope, two layers are presented in two different environments, cloud and client. In the cloud part, it is formed by different components that we can classify into two distinct layers: Data and Services. One entry point to the service layer is a broker [20]. This component allows connecting with different IoT devices by using multiple protocols. It can support some well-known protocols, such as Message Queue Telemetry Transport (MQTT), Advanced Message Queuing Protocol (AMQP) and Simple (or Streaming) Text-Oriented Message Protocol (STOMP). This broker is used as a link to connect the software platform-logic with IoT devices. There is a double connection between the two sides, and it can receive data from the IoT devices, as well as send data to them. The broker offers a message queuing system. It provides some benefits such as delivery order and delivery guarantee, redundancy, interface decoupling, flexibility and scalability.

The main component in the services layer is the Event-Driven-Application. It offers different capabilities or operations to fulfil all functional requirements. These capabilities have been divided into two distinct groups. The first group is the persistence layer to store permanent data from the perception layer and other generated data. These data are stared in the Data layer and are divided into two categories: counting data and auxiliary data. The first group consists of all the data provide by the IoT devices from the perception layer. The second group, auxiliary data, stores the maximum occupancy levels for each room to control. Finally, moving up to the top of the diagram, the software platform layer connects with the applications and business layer. This last layer will contain applications to visualise and interact with all the functionalities provided by software platform. This layer provides a productive and useful view for an end-user.

4. A technological solution

This section provides a technological proposal to clarify the agnostic concepts detailed in Section 3. In this way, two main components have been developed, the IoT detection device and a software platform. The hardware device is built using a micro-controller where two ToF sensors are connected. These sensors count when someone enters or leaves the room and is responsible for knowing at all times the current occupancy, and sends it to the server-side. The software platform has two main components: a pub-sub server, and a dashboard. The pub-server, hereinafter Broker, used to transfer messages between the detection device (the micro-controller) and the server-side. The server is also responsible to send to the micro-controller the maximum value, which is stored in the database. Data of the occupancy of the room is also stored in the database, in order to know the evolution of occupancy of the room with time. The dashboard displays all information generated, including the occupancy values and allows to manage capacity.

The following subsections describe at a technological level how each of the parts has been developed and the testing facilities. Figure 2 presents a general summary of all technologies used to develop the system.

4.1. IoT detection device

To create the prototype, we have opted to use an electronic board called *HiLetgo UNO R3 D1 R32 ESP32*. This electronic board includes an ESP32 processor that has WiFi and Bluetooth and is compatible with Arduino. Two ToF active laser infrared sensors that allow precise distances called VL53L0 model are used. A first prototype was made with ultrasound sensors connected to an Arduino UNO. This prototype provided a solution to the problem, but in a noisy environment, these sensors give false positives and false negatives making it very difficult to control and considerably increase the margin of error and reducing reliability. For this reason, the solution is finally implemented with sensors VL53L0X which are laser ToF.

The VL53L0X sensor is part of the new generation of ToF sensors. It offers accurate measurements regardless of the reflecting surface with a measuring range of $50\,\mathrm{mm}$ up to $2\,\mathrm{m}$. The principle of operation of this sensor is similar to that of ultrasonic sensors: the sensor has a laser emitter that emits a beam of light from time to time. When the laser reflects in an object, the sensor can measure the time between the emission and detection of light and since the speed of light is a known value, the distance to the object can be obtained applying kinematics:

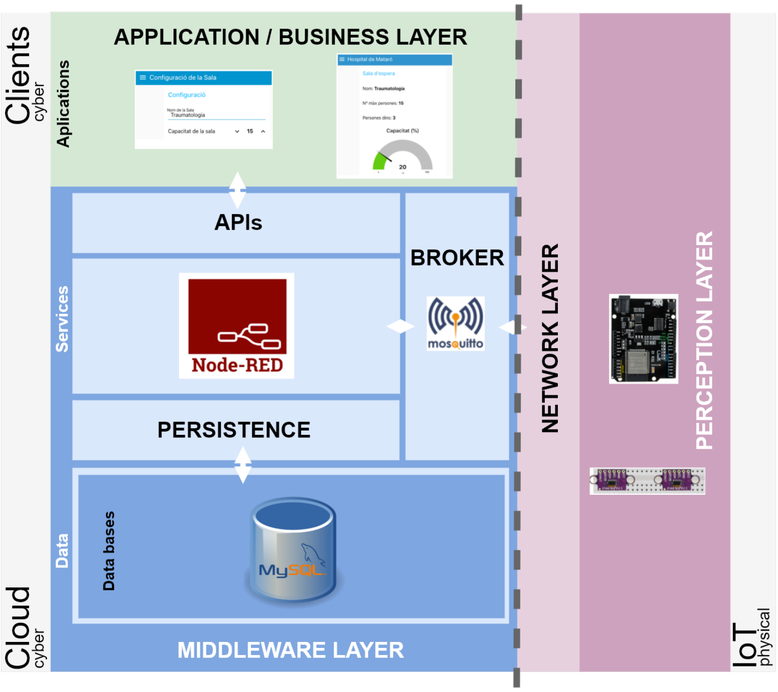


Figure 2: A general overview of the full system from a technological point of view.

$$distance = c \cdot \frac{time\,of\,flight}{2} \tag{1}$$

where c is the speed of light and $time_of_flight$ is the time between the emission and the measure. It is divided by 2 to take into account that the return trip of the beam.

The VL53L0X chip has been designed to work even when the ambient light is high. This is important because to work with optical measurements the greater the light pollution of the environment, the more difficult it is to properly capture the rebound of the signal.

The operation of the detection device is as follows: the micro-controller receives signals from both sensors when an object (a person) is placed in front of them. The first sensor that detects the obstacle gives information about if the person is entering or leaving the room. The micro-controller uses WiFi connectivity to establish a connection to the server-side. The pseudo-code for the behaviour of the device is shown below.

When the microcontroler starts, makes a query to the database and obtains the maximum number of people allowed and the number of people inside the room. This makes the system robust to unexpected reinitializations. These checks are programmed within the setup() function, as can be seen in Algorithm 1.

The cost for the implementation of the final prototype can be seen in Table 2.

Algorithm 1 Operation of the micro-controller algorithm

```
Declaration of required libraries
Definition of variables and objects
function Setup()
    Connecting the board to WiFi
    Connection of the board to the broker, at this point the topics to which you are subscribed are checked and the values in the database are retrieved, both of the people inside and the capacity of the room[1].
    Sensors initialisation
end function
function Loop()
    Check sensor distances
    if If the sensor 1 distance is smaller than the width of the passage then
        It means that someone is entering
    end if
    if If during 5 seconds the sensor 2 distance is smaller than the width of the passage after passing sensor 1 then
        It means that someone has entered, a new person is counted and the total is sent to the broker.
    end if
    if If the sensor 2 distance is smaller than the width of the passage then
        It means that someone is entering
    end if
    if If during 5 seconds the sensor 1 distance is smaller than the width of the passage after passing sensor 2 then
        It means that someone has left, a person is subtracted to the total people and the total is sent to the broker.
    end if
end function
```

Table 2
Cost of hardware components

Component	**Cost (€)**
HiLetgo UNO R3 D1 R32 ESP32 micro-controller	10.49€
DuPont cables	6.99€
VL53L0X ToF sensors	24.99€
Total	**42.47€**

4.2. Software platform: Eclipse Mosquitto and Node-RED

The micro-controller communicates via MQTT [20] with the server using the Broker. MQTT is a client-server message transport protocol based on publications and subscriptions called *topics*. This makes it suitable for IoT messages [2], as is the case with the interaction of low-power sensors or plates with micro-controllers. Specifically, it implements **Eclipse Mosquitto** as a broker which is open source (licensed EPL/EDL) and works with versions 5.0, 3.1.1 and 3.1 of the MQTT protocol.

The software used to deploy the even-driven application is Node-RED. It is a programming tool for interconnecting hardware devices, APIs, and online services. This tool allows to visually program a web browser-based workflow where nodes can be added or removed or connected to each other so that they can communicate among themselves in real-time.

Figure 3 shows a flow created with Node-RED. In the flow there are MQTT nodes that allow establishing a connection with the Broker, that manages the received and sent information; to establish a connection with the database, and to show and to collect information in the

---

[2] Grouping and interconnecting devices and objects over a network, where they can all be visible and interact.

dashboard.

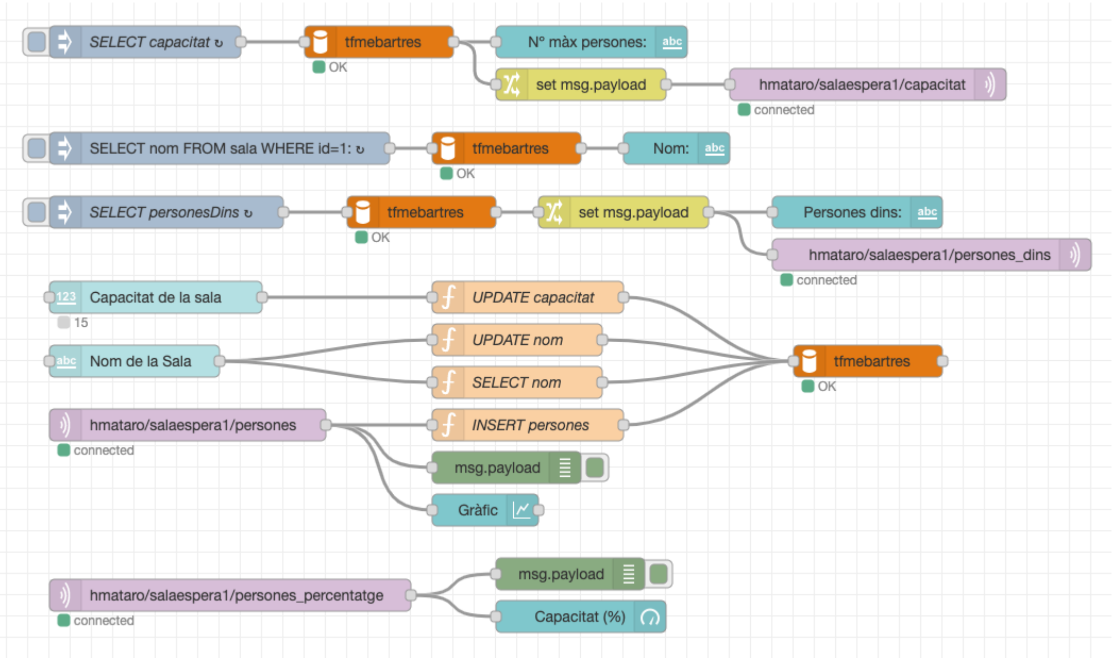


Figure 3: Flow created with Node-RED for the device.

To give consistency and traceability to the entire flow, the data collected by the electronic board through the sensors is stored in a database. This is a MySQL database and consists of two tables. The table **ROOM** where the *name* and the *capacity* of the room are stored and the table **PERSON** where the total people are stored (*peopleInside*) inside the room every time someone enters or leaves and the date and time (*dateTime*) at the time it passes. From Node-RED, records are inserted and consulted in the database. The following table shows the SQL statements [3]

When the Broker reports the people inside the room, the counter and the dashboard graph are updated. The dashboard is the graphical interface that is also generated with Node-RED, as can be seen in Figure 4. The dashboard contains information about the name of the room, the maximum number of people and the number of people inside. It also shows graphically the percentage of the capacity and a graphic that shows the evolution with time of the occupancy.

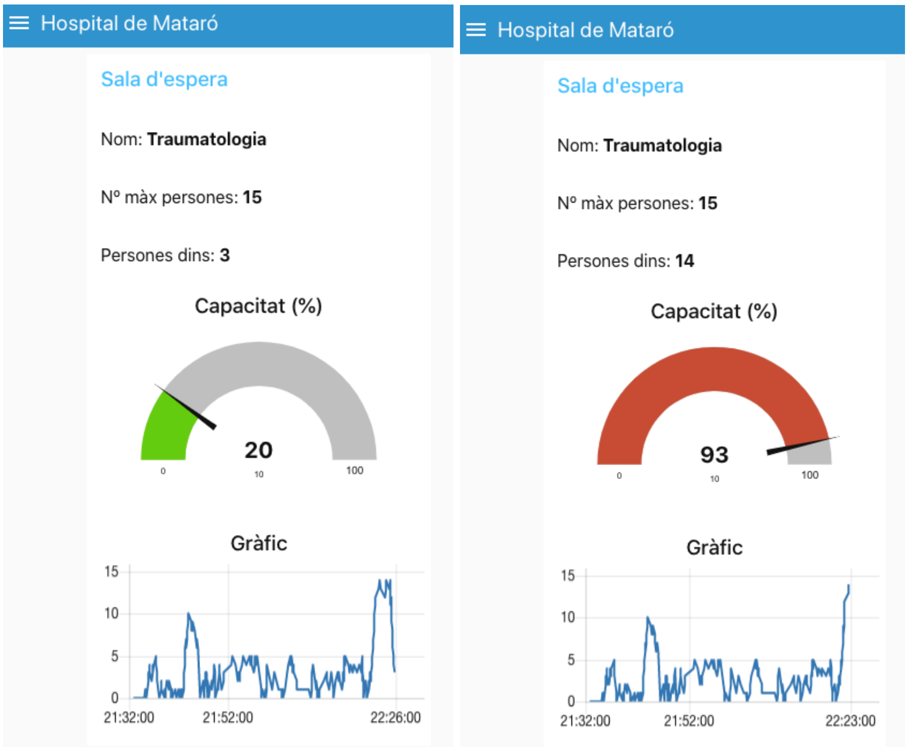
Since in this project all the software that has been used is open and free, in this aspect it is only necessary to take into account the expenditure on human resources.

4.3. A hospital room scenario

Due to the restrictions caused by the pandemic, the system was tested simulating a waiting room of the Traumatology section of Hospital de Mataró (Catalunya, Spain). The waiting room could not be real since the limitations and restrictions caused by COVID-19 did not allow us to take

---

[3] It is a standard language of communication with relational databases.



Hospital de Mataró

Sala d'espera

Nom: **Traumatologia**

Nº màx persones: **15**

Persones dins: **3**

Hospital de Mataró

Sala d'espera

Nom: **Traumatologia**

Nº màx persones: **15**

Persones dins: **14**

Figure 4: Dashboard created from the flux diagram of Node-RED

the test in a real waiting room with real patients. Therefore, the prototype was deployed in the door of a private room without real patients and the people who participated were collaborators. Figure 5 shows how the prototype was deployed.

The dashboard was displayed on a screen installed at the entrance of the room. Thus, anyone who wants to enter the room can see if the level of occupancy grant access to it.

A waiting room can contain any number of people between 0 and the maximum capacity. Patients or people can enter or leave the room at will, although they should not enter if the occupancy level does not allow it.

It is understood that patients and/or people who use the room can understand what they will see on the dashboard screen and will be able to interpret whether they can access or otherwise have to wait for the room to be released.

To analyse the data obtained in the experiment carried out, the methodology of the descriptive analysis is carried out that provides us with a vision that is made with the information provided by the data of a sample. That is, the purpose is to collect and order the information obtained and extract the most representative characteristics.

To check the reliability of the system, the level of occupancy obtained is compared with two the true occupancy of the room.

The waiting room is defined with a maximum capacity of 15 people and the entrance and exit of people are analysed normally, without applying any rules of access to the room.

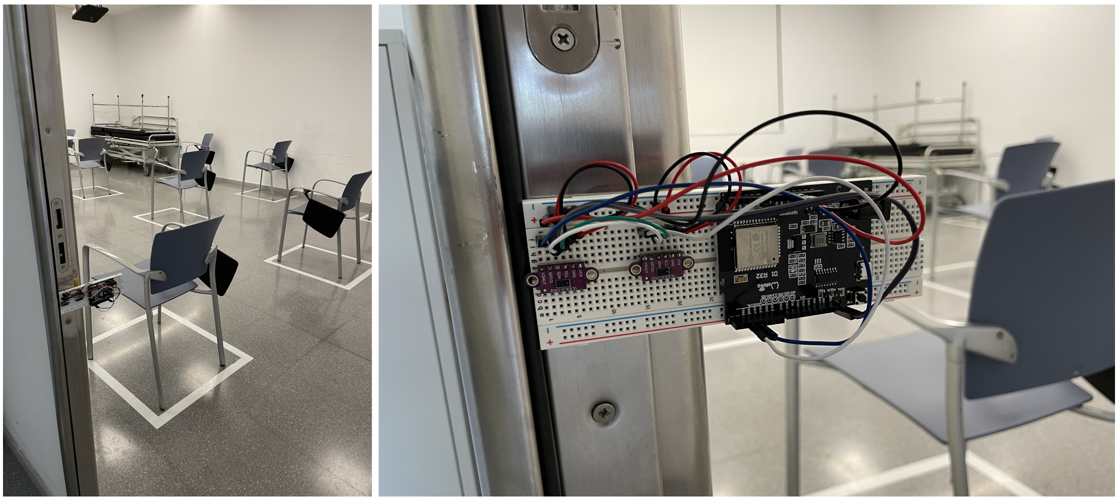


Figure 5: Picture with the prototype deployment in the hospital room.

Two different experiments were realised: 1) in the first experiment users are not told that a prototype is deployed; 2) in the second try, users are informed of the prototype, and given recommendations after analysing the results of the first test.

5. Results and discussion

During the experiment we obtain the following results: 1) when enters people until the maximum capacity of the room is achieved (15 people), 2 people were not detected, and 2) when 15 people leave the room, one is not detected and another one is counted as an entrance and an exit. Thus, the system successfully worked in 86.6% of the cases.

If we analyse deeply the cases in which the system failed, we find that, in the entrance, the first person that was not detected is because he or she enters very fast and, although the first sensor detected it, the second did not, and the prototype did not count anyone. In the case of the second undetected person, it was because two people came in together and the prototype detected only one.

On the exit, the first person who was not been detected was also because it left the room at the same time that another one and the prototype detects only one. In the second case, there is a person who has come out stopping right in front of the sensor and this has caused a false positive entrance, although the output was counted correctly.

The test was performed again, but this time users were informed about the room has a system to count people and that they must enter and leave the room one by one. With this recommendation, the system detects correctly all the people who enter the room and all the people who leave the room. Therefore, in this second case, the system successfully worked 100% of the cases.

6. Conclusions

This work presents a hardware and software solution to respond to occupancy control in indoor environments with a single entrance. The proposed solution is considered low-cost as it is made up of low price open hardware components, and the server part can be executed on any server, even on a microcomputer such as a Raspberry Pi. The prototype presented allows also to record the occupancy of the space at every moment. These data are stored in the database and every time someone enters or leaves the room the date and time and the people inside the room the information is updated. With this information, it is possible to extract information from when the room is busier.

Two experiments have been carried out in a simulated scenario. The first of them with an accuracy of 86.6% without warning the patients of the existence of the control system. The second experiment was carried out by indicating to the patients the existence of the system. In this case, a 100% success rate was obtained.

As future work, our first objective is to improve the prototype and provide a final product. In our roadmap, we have planned the design of a box to encapsulate all the hardware components used in the control device. At the same time, we want to carry out more exhaustive studies by deploying our proposal in more spaces and different environments. Finally, using the registered occupancy data we want to apply machine learning techniques for the prediction of occupancy to help decision-making.

Acknowledgments

Sergio Trilles has been funded by the postdoctoral Juan de la Cierva fellowship programme of the Spanish Ministry for Science and Innovation (IJC2018-035017-I). Joaquín Torres-Sospedra has been funded by the postdoctoral Torres Quevedo fellowship programme of the Spanish Ministry for Science and Innovation (INSIGNIA, PTQ2018-009981).

References

[1] G. Bonaccorsi, F. Pierri, M. Cinelli, A. Flori, A. Galeazzi, F. Porcelli, A. L. Schmidt, C. M. Valensise, A. Scala, W. Quattrociocchi, et al., Economic and social consequences of human mobility restrictions under covid-19, Proceedings of the National Academy of Sciences 117 (2020) 15530–15535.

[2] R. Abouk, B. Heydari, The immediate effect of covid-19 policies on social-distancing behavior in the united states, Public Health Reports 136 (2021) 245–252.

[3] D. S. W. Ting, L. Carin, V. Dzau, T. Y. Wong, Digital technology and covid-19, Nature medicine 26 (2020) 459–461.

[4] C. Granell, A. Kamilaris, A. Kotsev, F. O. Ostermann, S. Trilles, Internet of things, in: Manual of digital earth, Springer, Singapore, 2020, pp. 387–423.

[5] S. Trilles, A. Calia, Ó. Belmonte, J. Torres-Sospedra, R. Montoliu, J. Huerta, Deployment of an open sensorized platform in a smart city context, Future Generation Computer Systems 76 (2017) 221–233.

[6] H. Mohammadmoradi, S. Yin, O. Gnawali, Room occupancy estimation through wifi, uwb, and light sensors mounted on doorways, in: Proceedings of the 2017 International Conference on Smart Digital Environment, 2017, pp. 27–34.

[7] Z. Chen, Y. Wang, H. Liu, Unobtrusive sensor-based occupancy facing direction detection and tracking using advanced machine learning algorithms, IEEE Sensors Journal 18 (2018) 6360–6368.

[8] Y. P. Raykov, E. Ozer, G. Dasika, A. Boukouvalas, M. A. Little, Predicting room occupancy with a single passive infrared (pir) sensor through behavior extraction, in: Proceedings of the 2016 ACM international joint conference on pervasive and ubiquitous computing, 2016, pp. 1016–1027.

[9] X. Lu, H. Wen, H. Zou, H. Jiang, L. Xie, N. Trigoni, Robust occupancy inference with commodity wifi, in: 2016 IEEE 12th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob), IEEE, 2016, pp. 1–8.

[10] M. M. C. Bielsa, Llei de regulació administrativa d'espectacles públics i activitats recreatives, Activitat parlamentària (2009) 24–29.

[11] V. L. Erickson, S. Achleitner, A. E. Cerpa, Poem: Power-efficient occupancy-based energy management system, in: Proceedings of the 12th international conference on Information processing in sensor networks, 2013, pp. 203–216.

[12] S. Zikos, A. Tsolakis, D. Meskos, A. Tryferidis, D. Tzovaras, Conditional random fields-based approach for real-time building occupancy estimation with multi-sensory networks, Automation in Construction 68 (2016) 128–145.

[13] K. Sun, Q. Zhao, J. Zou, A review of building occupancy measurement systems, Energy and Buildings 216 (2020) 109965.

[14] M. Maaspuro, Infrared occupancy detection technologies in building automation-a review, ARPN Journal of Engineering and Applied Sciences 13 (2018) 8055–8068.

[15] V. Nguyen, M. Ibrahim, S. Rupavatharam, M. Jawahar, M. Gruteser, R. Howard, Eyelight: Light-and-shadow-based occupancy estimation and room activity recognition, in: IEEE INFOCOM 2018-IEEE Conference on Computer Communications, IEEE, 2018, pp. 351–359.

[16] L. Wu, Y. Wang, A low-power electric-mechanical driving approach for true occupancy detection using a shuttered passive infrared sensor, IEEE Sensors Journal 19 (2018) 47–57.

[17] Y. Zhao, P. Tu, M.-C. Chang, Occupancy sensing and activity recognition with cameras and wireless sensors, in: Proceedings of the 2nd Workshop on Data Acquisition To Analysis, 2019, pp. 1–6.

[18] M. M. Ouf, M. H. Issa, A. Azzouz, A.-M. Sadick, Effectiveness of using wifi technologies to detect and predict building occupancy, Sustainable buildings 2 (2017) 1–10.

[19] N. Li, G. Calis, B. Becerik-Gerber, Measuring and monitoring occupancy with an rfid based system for demand-driven hvac operations, Automation in construction 24 (2012) 89–99.

[20] D. Soni, A. Makwana, A survey on mqtt: a protocol of internet of things (iot), in: International Conference On Telecommunication, Power Analysis And Computing Techniques (ICTPACT-2017), 2017.