POLITECNICO DI TORINO

Master's Degree in Electronics Engineering

Study the feasibility of a system that detects the presence of people in hotel rooms to save energy when the rooms are vacated

Master's Degree Thesis

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In Loving Memory of Rosa, Carmenza and Carlos

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1. Introduction

Nowadays, people's needs have led to the study of new technologies and tools to solve problems. One of the problems that has been studied for decades has been the issue of position quantification, trajectories to follow in order to reach a desired place, among other questions that have been asked over time. Faced with these uncertainties, many tools have emerged to help answer and advance with these questions, such as maps, the development of geographic coordinate systems and one of the most prominent lately, is the popular *GPS (Global Positioning System)*. This particular technology has been developed to such an extent that every smartphone has this type of system, therefore, each person can have his or her location in real time, from anywhere in the world. [1]

But what happens if you are looking for the position of a person in a hostile environment, which is not common for *GPS*, such as closed spaces that are difficult to access for any person or contain a small space to work such as caves, or in work environments such as buildings, workrooms, food production processes, among others. Global positioning systems begin to show their limitations in this type of adverse situations, phenomena such as Multipath begin to occur (phenomenon that occurs when radio signals are received by the antennas by two or more paths and this at different times. This can cause problems when receiving the signals, as they can interact with each other. [2] This phenomenon itself occurs due to the multiple structures or surfaces on which the signal can be reflected, so in structures such as buildings, houses, warehouses, among others, the system would not work in the most appropriate way. Evidently, the development that has been had for the location in closed environments has gone further and have created systems like the differential *GPS*, which is a system that provides modifications to the receivers of *GPS* in order to deliver a greater precision to the calculation of position. But these systems raise its price to unsuspected levels, leaving it out of reach for the average user.

These limitations have led to the development of new technologies and more robust methods, which allow to cross out all the errors that are found when studying and developing global positioning systems, such as the location in enclosed spaces which previously had no provision for this, due to the various technologies that have been developed as time passed, such as the implementation of infrared systems, the development of wifi, the use of Bluetooth, as well as lesser known technologies such as UWB, RFID, WLAN, ultrasound.

A possible application for this technology is when you want to track certain objects that are inside an apartment, hotel, warehouse, house, palletizing plant. As well as human and here the challenge is that, to be able to indicate to the operator who is in a hotel, if the parts that the hotel has are unoccupied, in order to have an energy efficiency, either to inspect it. That the cleaning operator knows if a guest is inside the room and thus be able to perform the corresponding tasks or the simple fact that a guest has already left the room, extra taxes that can be made to the service charge if this has not left the establishment at the appropriate time, to generate some statistics of the guests and their behavior of stay in the rooms among others.

As mentioned in the previous paragraph, it is very important to address the issue of energy efficiency in confined spaces or enclosed spaces, but if these lead to energy expenditure by people or subcontractors, so the power to generate a plan or implement technologies to these, are of paramount importance, since today the power to generate an awareness of the environment seems essential. In hotels is an issue of great importance, due to the large expenditure of energy that this has, either by issues of lights and systems on constantly, or in areas such as air conditioning, lighting, water heating, and use of appliances, are of paramount importance, due to what currently arises from environmental awareness.

The implementation of new technologies to the systems in closed spaces is essential, due to the incidents that can occur within this, and for some time has been that in every hotel establishment, it is essential to have smoke detectors which can try to fight in the first instance any incident with respect to fire. [3] But, what would happen if, the inhabitants of this sector are located in their rooms? It is also important to have this information to know the capacity of the hotel and the number of people in the rooms in case of a traumatic situation such as a fire or the investigation of possible situations which could bring disasters both in the rooms and in the inhabitants of the rooms.

World Tourism Organization (UNWTO) [4] indicates that among the most important implementations that can be developed in the hotel environment is the implementation of new technologies, which bring energy savings between 20 to 40 %, all thanks to some practices implemented by people, but also largely to the new technologies that have been implemented over time. World Tourism Organization (UNWTO) [4]

But not only the power to implement technologies is important when creating and generating solutions to any situation, you also have to evaluate the context, for this situation the privacy is essential, not to incur in the privacy of the people who temporarily inhabit a room is a priority at the time of inhabiting these places, having as a priority in the creation and use of technologies in confined places to maintain the greatest protection for people, not using cameras, or recording situations which can greatly compromise the person.

The main objective of this project is to choose and analyze a device to be able to observe the viability and development of people within a hotel, thus reducing the energy expenditure that is had when performing this task. For the above mentioned, the following specific objectives will be taking into account:

- To generate a state of the art, which aims to correlate the previous work already done.
- To indicate until today the different devices on the market that are available for purchasing, what are their limitations, what are the accuracies, updated costs and installation.
- To address the specific case study and through a chosen sensor taking into account all the points mentioned above.
- To generate experimental tests with the technology to be used, having as parameter the hotel industry.

In order to generate a discussion of findings and conclusion, taking into account limitations, environmental needs and cost effectiveness.

2. State of Art

2.1. Overview of Indoor Human Presence Detection

Wireless indoor human presence detection technologies have developed in many ways, with various types of sensors being created to fit under different contexts. Technologies such as Wifi, UWB (Ultra Wide Band), Bluetooth, RFID, Zigbee, Lidar or time of flight (ToF) have been used to establish some human presence or activity detection. Each of these technologies has some characteristics, pros and cons that determine their suitability for a given environment and application. While some technologies like Wi-Fi and Bluetooth can take advantage of already deployed infrastructures, some other technologies like Lidar and ToF provide better accuracy but are likely to be more complicated deployments.

Generally speaking, these technologies function by having a signal sent and or received whereby triangulation, signal strength, and time delay methods can be used to provide a general idea of the location of the people. Any of the technologies will be selected taking into account the expected level of accuracy, the size of the system, the costs, the privacy issues, etc.

Section 4 provides some features of these technologies focusing on how they work and how they are accurate.

2.2. Energy Efficiency and Retrofitting Challenges in Hotels

Most postindustrial and progressive establishments tend to focus on energy efficiency and power conservation which helps in minimizing both operational expenses and the negative effect of those operations. Detecting the feasibility of installation of the human presence detecting systems when the rooms are not occupied is the core thesis of this paper. In recent years, hotel businesses have employed numerous programs and technologies aimed at improving their level of energy efficiency, which resulted in both lower costs and better environmental protection.

Occupancy sensors such as Time of Flight technology based or Passive Infrared (PIR) sensors have been becoming the new trend in technology. The sensors determine whether a space is occupied or not and this information is relayed to the systems such as lighting, heating, ventilation, air conditioning, etc... which manage these settings. Such measures reduce pollution in the environment as energy is only consumed when it is needed. hen necessary, significantly reducing waste.

Research studies suggest that including occupancy sensors allows for reducing energy use ages in hotel facilities by as much as 30 %. [5] This not only helps the hotel's environment consciousness, but also becomes profitability by a tremendous value overtime. Also, several hotels have reported the use of Energy Management Systems (EMS) that enable them to monitor and manage energy usage throughout the hotel properly. These systems focus on minimizing energy usage of hotels in all segments such as rooms and public areas. With the help of these systems working together with occupancy sensors, optimizations of heating, ventilation and air conditioning (HVAC) systems can be achieved that result in saving a lot of energy. Recent studies have shown the implementation of EMS in hotels can also reduce energy use by an extra 20 % in addition to that derived from the use of occupancy sensors.[6]

Another major development in this area has been the provision of energy efficient Light Emitting Diodes (LEDs) for indoor use embedded in motion and occupancy sensors to allow lights on only when people are present. Led bulbs are ultra efficient, up to 75 % more energy efficient compared to the conventional incandescent ones and have a much longer life. [7]

With the help of these lights configured with occupancy sensors, hotels can make the utmost Easier management of energy consumption, while ensuring that lights will shut off automatically whenever the rooms are unoccupied. Besides economic measures, the safety of guests and personnel is a perennial concern in the hospitality industry. The structure of fire safety systems is one area in which the advancement of technology has caused significant development. Modern fire alarms are now equipped with early detection devices, including smoke and heat detectors, which have been able to advance sensors that can sense specific gases and heat levels associated with fires. Such systems are more precise and swifter than their predecessors, enabling shorter response time and greater efficiency in the actual fire detection. In the USA in 2022, there were over 8.2 million fire department calls of which around 1.5 million incidents were treated as fire or fire related calls, resulting in most loss of property and life. Almost half of these fires, more than thirty percent, occurred in a confined or enclosed occupiable structure such as a hotel. [8]

The advent of intelligent fire detection systems not only brings about safety measures but also makes a step forward in the conservation of energy since automatic systems manage energy consumption more efficiently. To conclude, implementing such technologies as occupancy sensors, EMS or automated LED lighting systems assists hotels in not only increasing their energy efficiency levels but also gaining respect from their guests through provision of green and ergonomic spaces. The attention of this research to the implementation of a system that identifies people present in the hotel room is consonant with these modern strategies of energy efficiency and brings evident economic and ecological benefits.

There are various issues that require careful consideration in the process of retrofitting hotels to incorporate new technologies and increase energy efficiency. One of the main hurdles is the adoption of new technology since many hotels were built decades ago and were not necessarily benefited from these technologies which impact on the age old electrical and plumbing systems as well as the entire building in terms of remodeling to allow installation of advanced energy management systems like occupancy sensors, smart thermostats and automated lights. However, the hotel retrofitting process can be expensive and prolonged considering the number of renovations that require disruption of regular hotel activities. [9] Adding insult to injury, retrofitting presents financial challenges that discourage majority of the hotel operators but more particularly the small-sized operators due to the required initial cost of such improvements. For the U.S. Green Building Council [10], the cost for patching a building varies but can be between 20 and 100 dollars for each building area with the only factor influencing cost being the specific retrofit patch needed which also ties into the cost of renovations. This kind of financier arrangement discourages hotel owners from carrying out renovations that are due and that would have otherwise resulted in energy savings.

Besides these economic constraints, retrofitting often creates interferences in the processes within the hotels which affects the experiences of the guests and can in turn affect the revenue. Other construction activities, system additions, and renovations might necessitate the closure of specific rooms or general common areas for a certain period which can result in decreased bookings or displeasure from guests who expect to use the facilities without interruptions during their visit. There are planning and communication strategies that would help avoid such disturbances, however, there remains a constant difficulty in achieving success within the renovations and maintaining efficiency whilst being operational. [11]

Furthermore, there are some additional barriers as well resulting from the incorporation of new technologies into the already existing systems. However, engagement with a second option creates a mixture of old systems plus modern functionality in most hotels which presents issues on compatibility. For illustration, attaching occupancy sensors like the VL53L7CX to existing building management systems may require outside assistance and considerable effort to ensure effective operations and information exchange between systems. Staffing training becomes equally important for workers to be able to interact with such technologies. [12]

Regulatory compliance is critical to the art of hospitality as it guarantees the operation of hotels within the legal boundaries that have been set up to protect guests and staff members and enhance safety as well as environmentally friendly practices. Construction codes, regulatory conditions and safety standards, it is a reflective practice of delivering safe and comfortable accommodations. [13]

Finally, the retrofitting challenges must be within the limits which would go towards the sustainability goals as well as basic modern comforts of guests. Travelers are now more aware of the environmental concerns and expect the hotels to be environmentally friendly. Such heightened awareness adds further complications to owners of hotels who must consider the costs and other aspects of retrofitting against the expectations of their guests' sustainability. [13] Those hotels which in a successful manner deploy energy-efficient technologies and adhere to the trends can enhance their market image and attract eco-friendly travelers. Overall, overcoming these retrofitting challenges is important for the hotels aiming at improving their energy efficiency without compromising on the quality of the guest experience and operational performance of the hotel.

2.3. Privacy Concerns and Non-Invasive Solutions

When human detection modules come into play in confined spaces such as hotel rooms, privacy becomes a critical issue. Many detection systems, including the most common ones, which are cameras and microphones, are likely to raise such issues because they enable collecting sensitive details which can be intrusive to space. Thus, there is a need to look for such systems which can detect individuals efficiently but would not be violating privacy in the process.

2.3.1. Invasive Technologies and Privacy Issues

It is for instance possible to suggest that cameras, audio recorders, certain bio-metric sensors, and possibly some other technologies are very useful in identifying human activities, but their implementation also mostly contradicts human privacy. For example, cameras capture every detail of what a particular individual does and where he goes but also photographs things that should not be photographed, thus creating possible ethical and legal issues. Secret video recording of monitoring systems in private spheres like the inside of a hotel room is often considered as very embarrassing, thus causing unnecessary tension or phobia of being on constant watch. Continuous visual surveillance poses dangers of not only invading personal privacy, but also as risk to the subject as loss of confidential and sensitive footage could take place. [14]

Similarly, audio recording devices are capable of detect sound and conversations in detail, as it may contain and collect information that is intrusive. In exceptional situations where privacy is most desired such are hotel rooms, these systems are often regarded as excessive. Bio-metric technologies, like facial recognition or fingerprint scanning also face challenges of the same nature. They can accurately detect and identify a person, and it is easy to see how this type of information might cut across the expectations of privacy guests go with to a hotel.[15] This aggregation of sensitive biological data is rather alarming and one may feel concerned as to the protection, usage, sharing or abuse of the collected data, hence rendering these solutions unsuitable in many instances within the hospitality sector.

Considering these challenges, non-invasive invasions like Time of Flight (ToF) sensors or Passive Infrared (PIR) sensors provide reasonable alternatives. These technologies guarantee high reliability in the detection of human beings or their activities without disclosing any individual's characteristic or identifiable trait which is needed in the detection of presence; hence privacy is not violated. Such invasive methods do not record or handle personally identifiable information, and this significantly lowers the probability of breach of privacy and exposure of information. Accordingly, these sensors are most suited for use in places with high level of privacy requirements, like hotel rooms.

2.3.2. Non-Invasive Solutions: A Focus on ToF and Other Technologies

Apart from avoiding complication, privacy interference, these methods provide accurate identification of a human being. Of these, Time of Flight (ToF) is preferred since it can determine a person's presence without visually or physically identifiable information and features which are lacking in some of the other technologies. A ToF sensor works by pulsating infrared light and measuring the time it takes to return the light to the sensor, thus creating accurate distance measurements. This way, only distance data is collected making ToF appropriate for places like hotel rooms where subject privacy is required. [16] Many new studies reveal that systems based on ToF have a good potential for detecting room occupation and performing movement analysis while preserving the privacy of the people present in the room. [17]

Another non-invasive technology which has a good potential is Ultra-Wideband (UWB) which utilizes low energy short radio waves for movement and presence detection in being on active areas within. UWB has a high degree of accuracy in small spaces, and is able to go through barriers, making it helpful in locating individuals without requiring cameras or instruments, which can be intrusive. UWB systems can measure the time difference of signal reflections, similar to ToF, but are enhanced by a larger range in detecting minor movements like that of breathing. UWB also provides minimal risks to privacy because of the fact that it does not record any personal identifiable information. [18]

Radio Frequency (RF) sensing is another non-invasive technology focusing on the presence detection. RF systems operate by detecting alterations in the strength of a signal caused by its reflection from objects or individuals in a room. RF signals are capable of detecting motion and presence through the walls, making it very suitable and non-sensitive. RF sensing like UWB is devoid of images or sounds; hence there is an extra sense of privacy. On the other hand, RF may be less accurate in distinguishing between objects and people, depending on the environment. [19]

Zigbee, a low-power wireless communication technology, can also be employed for human detection. Zigbee sensors typically use signal strength measurements (RSSI) to determine whether a person is present in a room. Although Zigbee is less precise than ToF or UWB, its low cost and energy efficiency make it a popular choice for large-scale installations in smart buildings. Moreover, because Zigbee sensors do not record visual or audio data, they present minimal privacy concerns. [20]

Another technology that can be used to detect a human is low power Zigbee wireless communication technology. In the case of Zigbee, typically use signal strength measurements (RSSI) to determine whether a person is present in a room. Though being less accurate than ToF or UWB, the affordability and energy conservative aspects of Zigbee have suited for being deployed in smart buildings at scale. Additionally, Zigbee sensors do not capture visual or audio data which raises the privacy concerns very low. [20]

By concentrating on non-invasive technologies such as ToF, UWB, RF and Zigbee, it is feasible to create a human detection system with good reliability, plausible deniability since it has high non-invasiveness, and due to high accuracy, can be relied upon. Each of these technologies employ a tradeoff between accuracy and degree of invasiveness, therefore these technologies are applicable in those places such as hotel rooms where the privacy of individuals is of concern. A system in which ToF technology is incorporated to give high precision together with a modified UWB and RF crosses would be the most effective in any detection system as it limits the data collected without compromising on detection strength.

2.4. Potential Hazard Detection Applications

Sensor technology serves not only the objective of detecting a person in a room but is also highly useful in ensuring that potential hazards in confined areas like hotel rooms, workplaces, and medical facilities are well managed. Through the utilization of Time of Flight (ToF), Ultra-Wideband (UWB), Radio Frequency (RF), and Zigbee technologies, it is feasible to maintain the environmental conditions of the surroundings and prevent risks, thus, improving safety.

2.4.1. Detection of Environmental Hazards

The use of the ToF and other non-destructive technologies has one of the distinct advantages to assessing and finding dangerous environmental parameters like the level of temperature, humidity, or the existence of toxic substances. ToF sensors, in particular, are able to identify beginning stages of environmental shifts when the distance or amount of movement of certain objects changes which are likely to cause problems like blockage of air vents or abnormal room setups. It has also been shown that ToF sensors combined with environmental monitoring systems can enhance the early warning of dangerous situations considerably. [16] For example, in smart buildings, this capability ensures that the risk is addressed and the damages contained rather than the opposite some damages from the risk.

UWB and RF-based systems also play a crucial role in detecting hazards, UWB's ability to penetrate walls and track movements behind obstacles makes it suitable for detecting changes in structural integrity or monitoring areas for potential equipment failures. For example, in mining operations, UWB technology has been employed to detect hazardous movement in underground tunnels, providing early warnings of potential cave-ins or structural damage. [21]. This makes it exceptional for industrial environments where large machinery or confined spaces are common. [18]

2.4.2. Fire and Smoke Detection

ToF sensors can further be incorporated in systems for fire hazard integrity. Traditional fire detection measures rely on smoke detectors, while it is possible that ToF technology may augment fire detection capability by identifying changes in the shape or location of objects within a room. If a fire or smoke covers the area the sensor is supposed to observe, it would wait and ascertain the presence of these events, in order to qualify an alarm to be activated due to these features. It has been established through studies that ToF sensors integrated with regular smoke detectors perform better in terms of response time facilitating fire emergency evacuations and responses. [22] This hybrid method works as a two-way approach, which enhances detection further, since ToF sensors can be in the forefront of detecting any fire hazards.

Besides, Zigbee-based networks are very often applied in wireless fire alarm systems because of their low power and high reliability qualities. Zigbee sensors may be used in wide area fire detection systems where wired connection may not be feasible, and their mesh network capability enables wide area timely alerting of the regions. Integrating ToF sensors with Zigbee networks offers a Systematic solution for fire and hazards monitoring ensuring effective coverage even in confined spaces like hotel rooms or industrial areas. [23]

2.4.3. Fall Detection and Occupant Safety

ToF and RF sensors have been widely implemented in healthcare and elderly assistance facilities for the purposes of falls prediction, establishing patients' movement and sending alerts in case of irregular movements. The application of ToF technology makes it possible to notice sudden changes in height which may mean a patient has collapsed, while RF signals are able to detect the location of people in different rooms or behind walls for effective tracking of patients without compromising their privacy. [24] Research has demonstrated that fall detection ToF systems have the capability to differentiate intentional and non-intentional fall events averting misdiagnosis hence enhancing patient safety measures. [25]

Through the employment of non-invasive technologies such as ToF and RF, healthcare systems can have the patients under the care without being actively watched. This in turn permits the caregivers to react appropriately to threats that may arise, including the risk of falls without interfering with the privacy and decency of the subjects being observed.

2.4.4. Structural Integrity and Equipment Failure Detection

Equally, in workplace environments, safeguarding the structural integrity of the buildings and the operability of the equipment is indispensable in ensuring that accidents do not occur. Both UWB and RF technologies are very efficient in picking out the tiniest of movements and vibrations which could imply the forthcoming failure of the equipment or structural damage. The fact that UWB has a significant edge in terms of precision in the identification of minute variations in structure makes it appropriate for the surveillance of the equipment to inform the users about possible failures that may happen. [26] It is also possible to use the RF waves to know if there are hidden cracks or changes in the structure which pose a risk to the structures and give an immediate warning against critical seismic activities. [19]

In sum, it is feasible to create a risk detection mechanism that guarantees the security of enclosed spaces through a combination of advanced sensor technologies, such as ToF, UWB, RF, and Zigbee. These technologies are designed to give early notification of the likelihood of risks so as to avert accidents, fires, breakdown of equipment and other hazardous situations, while ensuring that monitoring which is intrusive is not done.

2.5. Time of Flight (ToF) Technology

ToF is a measurement technique that determines the distance between a sensor and an object by measuring the time it takes for a signal, usually a pulse of light or sound, to travel to the object and back to the sensor. It is widely used in applications of depth sensors, 3D cameras, and distance measuring devices. [27]

2.5.1. Principles of ToF Sensors

In the following detailed step-by-step, it is shown how this method works:

- Pulse Emission: A ToF device emits a pulse of light (usually infrared light) or an ultrasonic signal to the object of interest. [27]
- Pulse reflection: The signal reflects off the surface of the object and returns to the sensor. [27]
- Pulse Detection: The sensor detects the reflected signal.
- Calculation of Time of Flight: The time elapsed from the emission of the pulse to the detection of the reflected pulse is measured. Since the speed of the signal (light or sound) is known, the distance can be calculated. This because the characteristic equation to be able to obtain the distance is given by : [28]

$$Distance = velocity \cdot time \tag{1}$$

In this case, since the time obtained is for a trip to which it goes and returns, the equation would be as follows:

$$2 \cdot distance = velocity \cdot time \tag{2}$$

Adapting to the data that we have in signals or waves, we have that the speed, would be the speed of the signal and the time, would be the time in which it takes to come and go the signal, the time of flight, so the equation would be as follows:

$$distance = \frac{\text{Signal Speed} \cdot \text{Time of Flight}}{2} \tag{3}$$

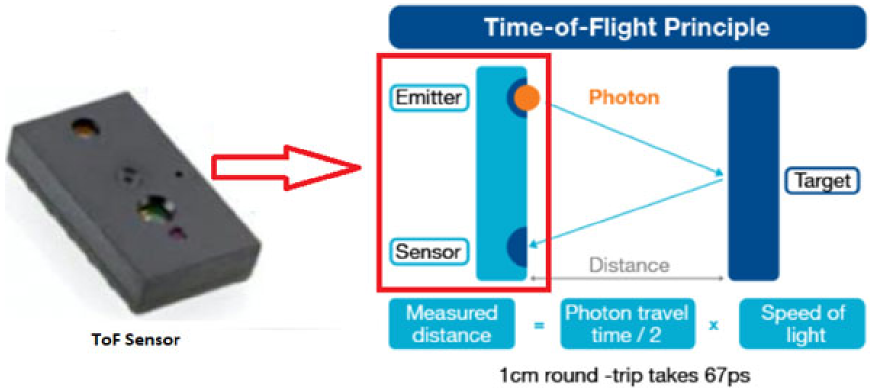

Fig. 1: Use of TOF technology. [29]

Some examples of where such estimates and technology are most useful include:

- 3D cameras: These are used to fit devices in the likes of smart phones and video games consoles to provide the depth mapping of the scenes and also enable gesture interactions with the devices.[27]
- Distance Measurement: In industrial automation, for precise distance measurement between components or for object detection purposes. [27]
- Human Machine Interaction (HMI): The primary function would be movement and gestures detecting especially and positioning in advanced user interfaces. [27]

There's no doubt that ToF imaging is one of the most reliable technologies for detecting a target within a certain range and for its comparison with other technologies it can be said:

- LiDAR (Light Detection and Ranging): ToF is similar to LiDAR technology in that it measures distances with lasers however; the use of LiDAR involves a greater expense and is usually found in autonomous vehicles.
- Ultrasonic: Compared to ultrasonic sensors that are low-cost but restricted to high-precision tasks, ToF is relatively higher in terms of resolution and measures density around accuracy levels.
- Stereo cameras: Unlike ToF, stereo cameras calculate depth using the disparity between two images taken from different angles, which can be less accurate in low-light environments.

In the current case, it is established that there are a good number of devices where this type of technology is applicable, many of them too are present in the manufacture of the component, as can be seen below:

- ToF Laser: Utilizes a laser light beam and creates pulses that can measure distances and is widely used for industrial and robotic purposes in medical, industrial, robotic and even space applications.

- ToF Cameras: Follows the same pattern as ToF laser; however this one adapter-sensor arrays that create depth maps. Presently, they are employed onboard smartphones, drones and augmented reality systems.
- Ultrasonic ToF: Sound waves are employed for measuring distances suitable for less complex systems such as parking sensors.

2.5.2. Applications in Human Detection

The **Time of Flight (ToF)** technology has received a further boost in effective human detection due to its precision in measuring distance by calculating how long it takes light to go to an object and come back. ToF sensors are designed to emit light pulses, most commonly in infrared, and these light pulses are used to determine time delays between the emission and reflection of light and thus determine distance. [27] Owing to this high accuracy of measurements, ToF is particularly effective for human presence detection any place for instance homes, buildings, industries, and healthcare areas. [30]

Automating systems such as lights and climate controls or security in smart homes and commercial buildings is one of the most practical uses of ToF technology. Through constantly assessing human presence and position in the room using ToF sensors, lighting systems can be improved by controlling the amount of electricity used when the room is occupied. [30] To offer an example, studies have reported a decrease in electricity use in smart lighting systems with ToF integrated within them by up to 30 % in the residential and small commercial environments. [5] Moreover, ToF based room occupancy monitoring also provides that the lighting and thermal control systems are set with respect to the number of occupants in the given room. [30]

In the field of human-computer interaction, gesture based handheld interaction with ToF based devices has become an essential form where a user controls the devices using human executable movements. ToF receptors are especially important for touch-less controls where a human utilizes movements for controlling an electrical gadget such as a TV, game console, and industrial control devices. For instance, Microsoft's Kinecty system is based on ToF capturing the actions of the body in three-dimensional space, enhancement percentages on several key measures were observed when the user interface and application worked seamlessly. [22]

A special application exists for ToF sensors, which is real-time monitoring of elderly patients' movements. The capability of recognizing falling or unusual body postures promotes the effective use of ToF sensors in circumstances that require quick caregiver response in case of an accident. Studies show that systems based on ToF technology are more accurate than traditional motion sensors. [25] These serve as the eyes of caregivers enabling them to have virtual babysitting while focusing on other duties and enhancing the security of elders living alone.

Security and surveillance systems also benefit from the use of ToF technology as well. ToF sensors create three-dimensional depth maps of environments, which make it easier to discover unauthorized human activities. This is quite helpful in environments with high security like banks, airports, and government buildings. Rather, ToF-based systems show good ability in differentiating between objects and humans in view of surveillance, hence lowering the probability of false alarms and general surveillance reliability. [31]

In the automotive industry, however, ToF technology has been employed in driver monitoring systems not only for performance but essentially for safety. These sensors monitor whether the driver is focused on the vehicle and these parameters can be extracted by the analysis of the driver's head and eye movements detecting drowsiness or distraction. ToF sensors are used for passengers detection in the vehicle and airbag deployment for safety improvements. [32]

In general, ToF technology is an effective, flexible, and energy-saving solution for human detection in diverse applications. Its capability to be used in different settings such as domestic and healthcare sectors, security, and even automotive sectors makes it a very useful technology that has the potential to improve human detection systems considerably. [31]

2.5.3. Comparison With Other Detection Technologies

When considering potential hazard detection and human presence monitoring, it would be reasonable to put ToF technologies, UWB, RF, and Zigbee technologies into comparison with such commonly used detection methods as video cameras or even bio-metrical systems. All the technologies listed have specific pros and problems which can be beneficial or challenging depending on the specifics of the deployment scenarios, environmental conditions, and privacy issues.

Cameras and Visual Surveillance

Cameras has become one of the most widely adopted technologies for surveillance and security and monitoring human activity. It also has a great advantage in the case of providing visual data, which can be extremely useful in detecting any sort of intrusion or fire, or any unauthorized activity. But these cameras do raise serious concerns about privacy, especially in enclosed environments like hospitals or medical facilities. Moreover, a person being video recorded 24/7, may find this situation to become unfavorable because the users might find themselves under constant observation and there's always the risk of private footage leaks. [14] Camera also faces the problem whereby, they need constant lighting or infrared features high low light settings, this causes a major drawback in regard to the power consumption.

In contrast, ToF, UWB, RF, and Zigbee technologies have the advantage of being able to monitor in a non-intrusive manner, which makes them more suitable for privacy-sensitive environments. These technologies do not capture images or video, significantly reducing privacy concerns. The Time-of-Flight in particular, offers high precision in detecting objects and movements without revealing any identifiable information about the individuals being monitored. [33] While cameras provide visual confirmation, nearly all non-visual sensors are able to cover many situations, without having to compromise privacy features.

Infrared Sensors and Motion Detectors

In human interaction and movements, motion detectors and infrared (IR) sensors have become quite useful in monitoring human presence and movement. These sensors detect the presence of a heat source or motion within a fixed area, which makes basic occupancy detection resourceful. Certain limitations also affect the IR sensors concerning range and operational accuracy such as in large areas or where minute actions must be performed. These detectors are also affected by false alarms that are typically induced by environmental changes such as temperature fluctuations and movements of inanimate objects. [34]

In comparison, ToF sensors offer much greater precision and range than standard IR sensors, enabling the detection of even small movements and changes in the environment.

ToF can measure distances with millimeter accuracy, making it more reliable for detecting hazards like fire or structural changes in a room. UWB also outperforms IR in confined spaces, as it can penetrate obstacles and walls, providing continuous monitoring even in obstructed areas [35].

In comparison, ToF sensors offer much greater precision and range than standard IR sensors, enabling the detection of even small movements and changes in the environment. ToF sensors have high levels of range precision, making it more reliable for detecting hazards like fire or structural changes in a room. UWB also bests IR for enclosed zones by being able to traverse barriers and walls thereby offering surveillance even where security is compromised. [35].

Ultrasonic Sensors

Ultrasonic sensors are also an option for monitoring human presence and motion patterns. These sensors send sound waves which help in assessing the existence of objects or individuals in the given space. Nonetheless, their non-invasive nature and lack of vision sensing capability is a drawback of limited range and accuracy mostly in scenarios featuring lags or shiny surfaces. Ultrasonic sensors in most cases, monitoring lacks the effectiveness of fine movements or scenarios that require real-time monitoring. [36]

Summary of Comparison

While visual technologies like cameras provide the advantage of real-time visual monitoring, they raise significant privacy concerns and are energy intensive. Non-visual technologies such as ToF, UWB, RF, and Zigbee offer a more privacy-friendly solution for human presence and hazard detection, mainly in closed spaces. ToF provides superior accuracy in measuring distances and detecting changes in the environment, making it suitable for hazard detection in personal or commercial spaces without compromising privacy. [27] UWB are particularly suited in situations where significant obstacles exist as they are able to maintain effective monitoring in difficult conditions while RF and Zigbee offer large-scale coverage but with a high-cost.

2.6. VL53L7CX Time-of-Flight Sensor

Another positive proposal in line with improving room monitoring systems is to integrate the VL53l7CX sensor which uses infrared technology and has the ToF measurement algorithm. This ToF sensor manufactured by STMicroelectronics has applications where accurate distance measurement is required through laser (infrared) technology. It is also held under the FlightSense™ family and addresses applications that require higher accuracy and faster response time in distance measurement such as robotics, mobile devices, smart appliances, and IoT applications. [37]

Some of its key features include:

- Distance measurement from a few centimeters up to 8 meters.
- High accuracy even in strong ambient light conditions.
- Ability to detect multiple targets simultaneously (multi-zone detection).
- Provides measurement data in 3D format, enabling surface mapping.

Fig. 2: VL53L7CX Time-of-Flight Sensor. [37]

2.6.1. Principle of Operation

The principle of operation is based on the Time of flight, as mentioned previously used to measure the distance between the sensor and an object. This sensor emits pulses of infrared laser light that reflect off nearby objects. The sensor records the time of light returning back the object and also calculates the distance by this data. The detailed step by step function standing at the work of this device is: [37]

1. The sensor emits an infrared laser pulse directed towards the target object. [37]
2. The laser hits the target and is reflected back to the sensor. [37]
3. The sensor measures the time it took for the pulse to travel from the sensor to the target and back. This time is translated directly into a distance measurement using the formula. [37]
$$Distance = \frac{\text{Signal speed} \cdot \text{Time of Flight}}{2} \tag{4}$$
4. Since light can be affected by different environmental factors (such as ambient light and surface reflection), the sensor applies correction algorithms to ensure measurement accuracy. [37]

With this measurement approach it is accurate, even on non-reflective surfaces and has the capability to perceive numerous objects in varying distances which is advantageous for applications requiring mapping and sensing in multiple regions. [37]

2.6.2. Technical Specifications

Among the technical specifications of this device are the following [37] :

- Contains a measurement range of 0.1 to 8 meters
- Can measure and perform measurements up to 64 zones (8x8 matrix) for multiple object detection.
- The resolution of the sensor allows measurements in intervals of less than 1 millimeter.
- The device is powered between 2.6 V to 3.5 V range.
- It has an I2C communication.

- It has a field of view (FoV): 60° x 60° (90° diagonal).
- The dimensions of the device are the following 6.4 mm x 3.0 mm x 1.6 mm.
- The power consumption of the device in continuous mode: Up to 266 mW with 2.8V power supply.
- The power consumption of the device in standalone mode is from 5.4 mW in low power modes (20 ms integration, 1 Hz in 4x4 mode).

2.6.3. Ranges and Accuracy

The ranges and precision possibilities contained in the device are as follows: [37]

- Maximum range (without ambient light, high reflectance), In 4x4 mode: up to 3500 mm with high reflectance (88 %).
- In 8x8 mode: up to 2000 mm with high reflectance.
- In close range (20-200 mm): ±9 mm error in dark conditions.
- At extended range (up to 4000 mm): Error of ±3 % to ±6 % depending on ambient light conditions and lens reflectance.

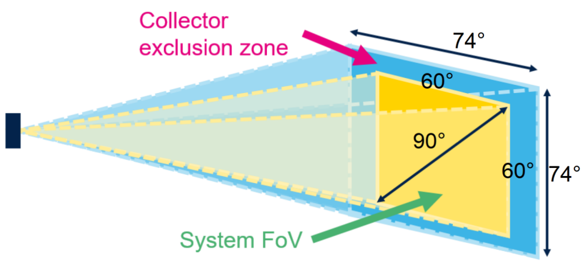

Fig. 3: System FoV and Exclusion Zone Description. [37]

2.6.4. Block Diagram VL53L7CX

To facilitate the comprehension of how the VL53L7CX device operates and its pin-out, we are going to elaborate its internal behavior, outlining how each of the pins embedded in the device works, all this is provided by the datasheet of the device. [37]

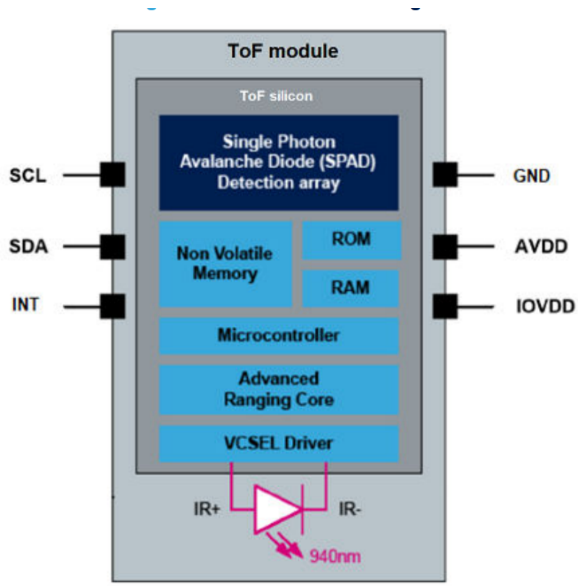

Fig. 4: Block Diagram VL53L7CX. [37]

The **Single Photon Avalanche Diode (SPAD) Detection Array** is a very sensitive detection array which can measure the arrival of a single photon allowing for high accuracy in determining the round-trip light time to the object. [37]

The **Non Volatile Memory** is read-write and allows the permanent device setup, such as the sensor firmware and calibration parameters to be saved, while the **Read Only Memory (ROM)** stores the necessary routines for sensor operation. [37]

The **Random Access Memory (RAM)** stores the measurements and calculations temporarily until the sensors' operations are completed. All internal processes of the sensor are managed by the integrated **Microcontroller** that also receives data from the SPAD array and commands main system communications. [37]

The **Advanced Ranging Core** is an advanced distance measurement core that performs precise calculations based on the data provided by the SPADs. In this core, other features such as complex algorithms are integrated in order enhance the accuracy and multiple zones of detection are handled at the same time. [37]

The **VCSEL Driver** controls the **VCSEL (Vertical Cavity Surface Emitting Laser)**, a laser that emits infrared light with a wavelength of 940 nm. This infrared light bounces off objects in front of the sensor, and the time it takes to return is measured to calculate distance. [37]

Pins: The **SCL** and **SDA** pins enable I^2C communication between the sensor and other devices, such as an external microcontroller. The **INT** (interrupt) pin notifies the main system when new data is available. **GND** is the system's ground connection, while the **AVDD** and **IOVDD** pins provide the necessary power for sensor operation. [37]

2.6.5. Use Cases and Applications

VL53L7CX sensor that incorporates Time of Flight (ToF) technology has a wide range of uses and applications other than just energy efficiency and people detection, hence making it ideal in different sectors. One of the applications is in industrial automation and robots.

Since the VL53L7CX sensor measures distance with a precision of about many millimeters, it can be effectively applied for robotic navigation and obstacle avoidance. [38]

In automated factories or warehouses, the sensor can be integrated into robotic systems to ensure safe navigation through environments and even adjacent workers, to avoid any collisions with obstacles. The fast response time and multi zone detection of the sensor allows robots to adjust their movements in real time, thus improving work efficiency and safety in fast changing environments. [38]

Another major area is in the use of VL53L7CX sensor in human gesture recognition systems that are also gaining popularity in devices such as smartphones and gaming consoles. The VL53L7CX can detect hand movements or gestures and uses this for the control of devices without touching them. In this application, the advantages are prominent in the areas where it is necessary to maintain hygiene (medical facilities, public places, etc.) as users do not need to come into physical contact with a device. [22] Because of their compact size and high accuracy, sensors can also be integrated into small consumer devices.

In autonomously driving vehicles and drones, the VL53L7CX is of particular importance for distance measurement and terrain mapping components. With the sensor being able to measure several meters away with plenty of accuracy, it can assist in 3D mapping and rendering which is critical for area navigation. For the drones, the use of the sensor can aid in hovering at an altitude and for collision avoidance during the flight which is required for safe and efficient operation when indoors or outdoors. [39]

The VL53L7CX is also used in industrial level sensing applications. In factories, the control device can be fitted in the production process to measure gaps in machine parts where the sensor can assist in determining if there are any objects present on the assembly line. The high dust or poor light environments doe not pose a major challenge for the sensor, its usage would help maintain the industry's precision. [38] In addition, this sensor also comes with a multi-zone feature that facilitates monitoring of many areas at the same time making it perfect for quality control applications requiring such capabilities to ensure that the same parameters are met over time. [37]

Moreover, the sensor can also be used in smart home systems where it serves a variety of purposes including proximity detection that controls automated doors, lighting systems, and security systems. The VL53L7CX, for instance, can enable automatic doors to open when someone tries to enter, and enable some lights to adjust brightness according to the distance of a person from the lights. [40] This makes the smart home technologies and activities that involve them more seamless and conserve energy. [7]

In summary, while the VL53L7CX sensor is highly effective in detecting human presence for energy-saving purposes in hotels, the applications of the sensor are broad and include: robotics, gesture recognition, autonomous navigation, industrial automation and smart home technologies. It is a seemingly accurate, fast and flexible tool suitable for multiple environments, and therefore, its use is not limited to the detection of occupancy alone.

2.6.6. Performance in Various Environments

Different factors such as the environment have an impact on the performance of the VL53L7CX sensor, for example, in the low light environment such as the nighttime in a hotel room or in a dim corridor the VL53L7CX does well since it is not dependent on ambient light.[37]

Presence and motion detection using the infrared light makes the sensor effective for nighttime where energy efficiency and security matters.Studies show that ToF sensors are highly effective in low-light conditions due to their reliance on infrared technology rather than visible light. [34]

Operating in reflective environments like hotel rooms which have some large windows or metallic objects, some ToF sensors might struggle with signal reflection, potentially affecting accuracy. The VL53L7CX on the other hand has advanced algorithms that eliminate the effects of materials used that are reflective and cause false readings. They can still be reliable but are said to perform poorly in extremely reflective environments but are calibratable to overcome such effects. [37]

In crowded or multi-occupant environments, such as hotel lobbies or conference rooms, the VL53L7CX excels at detecting multiple individuals simultaneously, thanks to its multi-zone capability. [37]

The sensor distinguishes between people in a room to activate lighting and HVAC (Heating, Ventilation, and Air Conditioning) only when there are active occupancy. Such systems reduce energy losses during events or peak hours when inside common areas, this is ideal for efficiency. It is also remarkable how due to the very wide FoV (Field of View) of the sensor, a smaller number of sensors are required hence making it more economical when there is a need to observe larger areas. [37]

In spaces where the electromagnetic interference level is high, such as where many electronic devices are situated, the VL53L7CX may experience interference that could impact its performance. Optimal accuracy can be achieved with care in sensor location and isolation from high electric and magnetic field strengths. Under this condition, however, most of the time, the sensor does work in quite a satisfactory manner in most hotel environments where such interference is minimal. [37]

Overall, due to its ability to work optimally under various conditions present in the hotel environment, VL53L7CX can be employed in circumstances with even greater energy efficiency by improving the reliability of human presence detection in the private or public areas of the buildings.

3. Methodology

Based on the main objective of this document, the following methodology is developed to meet the project's objectives. The methodology will follow a research-based approach, combining a Systematic Literature Review (SLR) with practical implementations, ensuring that both theoretical and experimental findings are well-supported.

3.1. Systematic Literature Review (SLR)

A systematic review was conducted to identify existing technologies and methods for detecting people in confined spaces using sensor-based detection. The following steps were followed to ensure a structured and unbiased review of the literature.

3.1.1. Search Strategy

The search strategy focused on peer-reviewed articles, conference papers, and technical reports published in the last ten years (2014–2024) related to detection technologies in confined spaces. Keywords used in the search included confined space detection, sensor technology, Wi-Fi detection, UWB detection, Zigbee presence detection, RF presence detection, and Time of Flight (ToF) detection. The databases consulted were IEEE Xplore, ScienceDirect, Google Scholar, and SpringerLink. Boolean operators (AND, OR) were used to refine the search and ensure a comprehensive collection of relevant studies.

3.1.2. Inclusion and Exclusion Criteria

Inclusion Criteria:

- Studies published in the last ten years (2013–2023).
- Articles focusing on the application of sensors for the detection of individuals in confined spaces.
- Studies that provide comparative analysis or case studies on the effectiveness of technologies like Wi-Fi, UWB, Zigbee, RF, and ToF.

Exclusion Criteria:

- Studies not focused on confined spaces or human detection.
- Papers that only discuss theoretical models without any practical or experimental validation.
- Duplicates or articles that lack technical depth or insufficient information.

3.1.3. Data Extraction and Synthesis

The selected papers were analyzed to extract key data related to the technologies used, their performance in confined spaces, and their limitations. Data extraction focused on the following points:

- Technology type (Wi-Fi, UWB, Zigbee, RF, ToF).
- Detection accuracy, range, and robustness.
- Challenges faced in confined spaces (e.g., signal interference, material absorption).
- Energy consumption and scalability.
- Cost of implementation.

A synthesis of the data was performed by comparing the key characteristics of each technology. This helped in identifying the most suitable technologies for further analysis and practical testing in confined spaces.

3.2. Comparative Analysis Framework

The Comparative Analysis Framework is designed to evaluate and compare the technologies identified through the systematic literature review. The aim is to select the most appropriate technology for detecting people in confined spaces based on a series of established evaluation criteria.

3.2.1. Evaluation Criteria

The following criteria were used to assess and compare each technology:

- **Detection Accuracy**: Ability of the technology to detect the presence of individuals with minimal errors.
- **Robustness to Environmental Conditions**: Performance in various environments, such as areas with metallic surfaces, high humidity, or confined geometry.
- **Scalability**: Ability of the system to be expanded or scaled for larger spaces.
- **Energy Efficiency**: Power consumption of the sensors during operation and in standby mode.
- **Cost of Implementation**: Total cost of installing and maintaining the sensor network.
- **Ease of Installation**: Complexity involved in deploying the sensors in confined spaces.
- **Privacy Considerations**: The extent to which the system ensures individual privacy without gathering unnecessary data.

4. Comparative Analysis of Detection Techniques

When one speaks of location, a map immediately comes to mind with a graphical interface indicating where a certain device is located or where a person is located. Localization is the location that an object or person has in a certain space. It requires coordinates that provide reference points for it to be traceable and communicable (Editorial. 2014). [1]

As these types of technologies have been developing, they have been classified into different types of positioning, all this according to how they work and how they base their type of communication. These can be classified as:

- Satellite positioning.
- Positioning based on communication networks.

GPS (Global Positioning System) is a worldwide navigation system. Currently, this system is composed of 24 artificial satellites and their respective stations that are located on the earth, providing positioning information 24 hours a day (L Casanova, 2002). Its operation is based on the measurement of distances from radio signals transmitted by a group of satellites, whose orbit is precisely known, and these signals are captured and decoded. [41] Once this information is obtained, satellite trilateration is used to determine the exact location of the target.

As shown in Figure 5, trilateration works by calculating the distances from at least three satellites to a specific point on the Earth's surface. Each satellite provides a distance measurement, which forms a radius around the satellite. The intersection of these radii, as represented in Figure 6, reveals the position of the target on the Earth's surface. This method is essential for accurate *GPS* positioning, as it relies on multiple reference points to pinpoint the location precisely. [42]

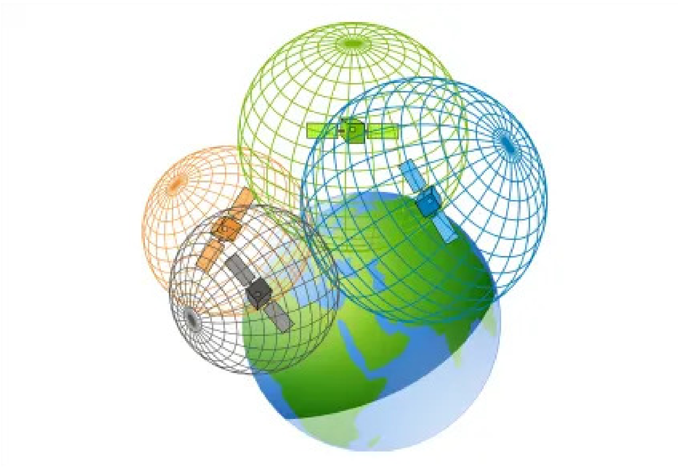

Fig. 5: Satellite Trilateration. [42]

Positioning based on communication networks is based on signals, which can be found in mobile networks, local wireless networks, as well as by sensors in ad-hoc networks. Some examples of communication types are:

- Systems based on infrared radiation: it is a simple structure, low cost and easy mobility, for the detection or tracking of objects or people. [43] They are used in both wireless and wired devices.
- Ultrasound based system: is a technology that uses ultrasonic waves, this allows measuring the distance between the fixed station and the mobile device to be located [44],
- Radio Frequency (RF) based system: mainly used in internal positioning systems, where electromagnetic waves can travel through walls, objects and human bodies. [45]

In order to be able to communicate between different devices, different techniques have been developed over the years to perform this action. When determining the location between a device that may be miles away, the best way to establish this type of communication is through wireless access technologies. The following list will define several of these technologies and show their respective characteristics, advantages and disadvantages. Among some of these can be found:

4.1. WiFi

Known wireless communication technology based on the 802.11 standard and protocol, which allows local networks, commonly used equipment in homes, such as computers, tablets, smartphones or cell phones, make use of radio frequencies for the transmission of information or connection between the same devices, generating an access point between them. [46]

4.1.1. Detection Principles

The principle behind Wi-Fi-based detection relies on measuring the Received Signal Strength Indicator (RSSI) from various Wi-Fi access points. Each access point emits a message constantly, which is received by the user's device. By measuring the received power, it is possible to estimate the location of the device. Triangulation or trilateration methods are typically employed, where the distance from multiple access points is calculated and combined to pinpoint the device's location. [42]

4.1.2. Accuracy and Robustness

Wi-Fi-based detection technologies generally offer moderate accuracy in location estimation, with typical accuracy ranges of about 3 to 5 meters, depending on the environment. Factors such as interference, signal reflections, and obstacles (like walls or furniture) can impact performance, making Wi-Fi less robust in complex environments [46]. Although Wi-Fi-based solutions work well in open areas, accuracy may degrade in highly obstructed environments like dense urban buildings or indoor settings with many partitions. [47]

4.1.3. Scalability and Complexity

One of the key advantages of Wi-Fi-based systems is their high scalability. Since Wi-Fi infrastructure is already present in most buildings, scaling these systems to cover larger areas or multiple rooms is straightforward. However, the complexity increases when attempting to achieve high accuracy, as it requires fine-tuning and possibly fingerprinting techniques, where a database of signal strengths is created to improve location estimates. This calibration process can be time-consuming and complex, especially in large or highly variable environments. [47]

4.1.4. Cost and Installation Requirements

The cost of implementing Wi-Fi-based detection is relatively low, especially in environments where Wi-Fi infrastructure is already present. Most modern buildings and homes are equipped with Wi-Fi access points, meaning that the installation costs are nearly zero. [48] The main investment is in calibration, which may require the creation of signal strength maps and adjustments to improve accuracy.

4.1.5. Privacy considerations

Privacy concerns are a significant issue with Wi-Fi-based detection technologies. Since Wi-Fi signals can easily penetrate walls and are constantly broadcast, there is a risk of unintended tracking or location estimation beyond the intended area. The passive monitoring of devices without explicit consent may raise ethical and legal concerns, especially in settings like hotel rooms or private homes where privacy is critical. [49]

4.1.6. Risk of Detection Outside the Room

Due to the nature of Wi-Fi signals, which can penetrate walls and travel significant distances, there is a high risk of detecting devices outside the intended area. For instance, a Wi-Fi-based system designed to detect occupancy within a hotel room might also detect devices in adjacent rooms or corridors, reducing the accuracy of room-specific occupancy detection. This issue can complicate the deployment of Wi-Fi for fine-grained location-based services where room-level accuracy is required. [50]

4.2. UWB

UWB (Ultra-wide-band) is a low power, short range, high data rate (480 Mbits/s) wireless technology. It emits Radio Frequency (RF) signals, which transmit binary data with low power consumption and very short duration or bursts of pulses across a frequency spectrum. Potentially, UWB signals consist of a bandwidth greater than 500 MHz. [51]

4.2.1. Detection Principles

UWB uses short-duration radio frequency pulses to detect movement and presence by measuring the time of signal reflection. UWB is particularly effective for precise movement detection, as its ability to emit extremely short pulses allows for accurate distance measurement. [51]

4.2.2. Accuracy and Robustness

UWB offers centimeter-level accuracy, making it one of the most precise technologies for detecting people, its high precision makes UWB suitable for applications requiring accurate movement and location detection, even in challenging environments. [51]

4.2.3. Scalability and Complexity

While UWB is scalable, its installation requires specialized infrastructure, making it expensive and complex due to the need for specialized equipment, limiting its use to high-precision applications. [52]

4.2.4. Costs and Installation Requirements

UWB has a high installation cost because of the advanced infrastructure it requires. UWB is highly accurate, its cost can be prohibitive for more common applications, limiting its use to environments where extreme precision is necessary. [52]

4.2.5. Privacy Considerations

UWB is a privacy-safe option as it does not collect personal or identifiable information, which minimizes privacy concerns. UWB became well-suited to the requirements of hospital settings, ensuring patient safety and operational efficiency. [53]

4.2.6. Risk of Detection Outside the Room

UWB signals can penetrate walls, posing a small risk of detecting individuals outside the room. As states by Kocur, D et al UWB radar measures with high rate and it can continually track people even in the case when their radar echoes are crossing or merging. [54]

4.3. Bluetooth

Bluetooth is a communications protocol used for wireless transmission of data (photos, music, contacts, etc.) and voice between different devices within a short distance, usually within a perimeter of ten meters. One of the applications that have been developed through this technology, is to be able to link the smartphone with a printer in order to print the photos contained in that device without the need for cables. [55]

4.3.1. Detection Principles

Bluetooth technology uses Received Signal Strength Indicator (RSSI) to detect the presence of nearby devices, allowing the calculation of distance and determining if a person is present. Bluetooth-enabled devices emitting signals, can be triangulated to estimate the location of individuals. [56]

4.3.2. Accuracy and Robustness

Bluetooth accuracy ranges from 1 to 10 meters, making it suitable for proximity-based applications rather than precise localization. However, Bluetooth shows limited accuracy, especially in environments with multiple obstacles or interference. [56]

4.3.3. Scalability and Complexity

Bluetooth is highly scalable since most modern devices are already equipped with this technology, making it easy to implement on a large scale. **zhangbluetooh2020encyclopedia**

4.3.4. Costs and Installation Requirements

It is a low-cost solution due to its widespread adoption. Bluetooth requires minimal investment for implementation, since most devices are already equipped with this technology, like smartphones, computers, radio and even smart TVs. **zhangbluetooh2020encyclopedia**

4.3.5. Privacy Considerations

Although it does not capture images or audio, continuous signal monitoring may raise privacy concerns, due to the potential tracking of personal devices without user consent. [57]

4.3.6. Risk of Detection Outside the Room

Bluetooth signals can penetrate walls, posing a moderate risk of detecting individuals outside the room if the system is not properly calibrated, this may compromise detection in unwanted areas. [55]

4.4. RFID (Radio Frequency Identification)

This technology is used to identify some object or element, follow its movement route and calculate distances thanks to a special tag which emits radio waves, this is attached or incorporated to the object. In order for the user to know the location, it need to have a number of radio frequency tags nearby. RFID technology allows tags to be read even when they do not have a direct line of sight and can also penetrate layers that are quite thin. [58]

4.4.1. Detection Principles

RFID technology relies on tags that communicate with readers via radio waves. The tag emits a signal, which the reader picks up and decodes to identify the tagged object or person. The readers can be fixed or mobile, depending on the application, and they collect data passively from the tags. RFID typically operates in the UHF or LF frequency ranges, which allows for flexible deployment in both short- and long-range applications. [58]

4.4.2. Accuracy and Robustness

The accuracy of RFID can vary significantly depending on the type of tag and reader used. For indoor environments, RFID systems generally have an effective range of 2 to 3 meters, but accuracy can be influenced by signal interference or the presence of materials that block radio waves, such as metal or water. However, RFID is considered a robust technology because it functions without requiring a direct line of sight, which is an advantage over technologies like infrared or optical systems. Despite this, RFID can still experience reduced accuracy when signals are obstructed or reflected by surrounding materials. [59]

4.4.3. Scalability and Complexity

RFID is highly scalable, as it allows for the simultaneous identification of multiple tags, making it useful in large-scale environments such as warehouses, retail stores, or even hospitals. The scalability of RFID largely depends on the number of readers deployed, however, RFID tags are inexpensive, the complexity of the system increases with the need for additional readers to cover larger areas, which can raise installation costs and maintenance complexity. For smaller-scale applications, fewer readers are required, which simplifies implementation. [60]

4.4.4. Cost and Installation Requirements

RFID tags themselves are generally low-cost, making the technology affordable for tagging and tracking many objects or individuals. However, the cost of RFID systems rises with the infrastructure required, specifically the number of readers and the networking needed to connect them. The installation of RFID systems also requires careful calibration to ensure proper coverage, especially in environments where interference may be an issue. [60]

4.4.5. Privacy Considerations

While RFID does not capture images or audio, which minimizes certain privacy concerns, it can still raise significant privacy issues. it is believe that RFID systems can track tags from a distance, potentially compromising privacy if individuals are unaware that their tags are being scanned. The passive nature of RFID means that users may not know when they are being tracked, raising ethical concerns about surveillance in public and private spaces. [61]

4.4.6. Risk of Detection Outside the Room

RFID particularly suitable for room-level detection, where the risk of detecting people or objects in neighboring rooms is minimized. RFID's range is relatively limited compared to other detection technologies, which reduces the risk of unwanted detection in adjacent areas. Although certain materials, like metal, can block RFID signals, the overall risk of detecting tags or individuals outside the intended detection zone is generally low. [62]

4.5. Zigbee

Zigbee is a low-power wireless communication protocol commonly used for home automation and sensor networks. It detects the presence of people through motion sensors or by measuring disturbances in signal strength. Zigbee operates in the 2.4 GHz frequency range, providing a balance between range, power consumption, and data rate, making it well-suited for low-power applications. [63]

4.5.1. Detection Principles

Zigbee technology is typically connected to motion detectors, such as passive infrared (PIR) sensors, which detect human presence by sensing movement. The PIR sensors measure changes in infrared radiation emitted by objects or people, and Zigbee is responsible for transmitting this data to a central system. [63] Zigbee can also measure changes in signal strength to detect disturbances in the environment, which can indicate movement. While Zigbee's detection principles are sufficient for basic occupancy sensing, it lacks the detailed precision of other technologies like Ultra-Wideband (UWB) or Time of Flight (ToF). [51]

4.5.2. Accuracy and Robustness

The accuracy of Zigbee is generally in the range of a few meters, making it adequate for applications where high precision is not essential. [64] Zigbee's primary advantage lies in its robustness for low-power and large-scale deployments, but its accuracy can be influenced by interference from other wireless networks operating in the same frequency band, such as Wi-Fi. [51]

4.5.3. Scalability and Complexity

One of the key strengths of Zigbee technology is its scalability. Zigbee networks can be easily expanded to cover large areas, with minimal infrastructure costs. As a mesh network, Zigbee allows multiple devices to act as nodes that can relay data to each other, enabling wide coverage even in complex environments. [23] The low complexity and low-power consumption of Zigbee make it particularly suitable for battery-operated devices, such as motion detectors and door sensors in smart homes or industrial settings. Its ability to form self-healing networks also enhances its scalability, as devices can automatically reroute data if a node fails. However, compared to technologies like Wi-Fi or UWB, Zigbee offers lower bandwidth and slower data rates, which may limit its use in high-demand applications. [51]

4.5.4. Cost and Installation Requirements

Zigbee technology is cost-effective, particularly for large-scale installations. Since Zigbee operates on low power, the devices typically have long battery life, reducing maintenance costs. [23]Additionally, the infrastructure required for Zigbee networks is minimal, as its mesh network architecture allows each device to communicate with others, reducing the need for central hubs or repeaters [63]. This makes Zigbee an attractive option for smart buildings and home automation systems, where the focus is on low-cost and energy-efficient solutions. The installation process is relatively straightforward, as the devices can be easily integrated into existing networks without major infrastructure changes.

4.5.5. Privacy Considerations

Zigbee does not either capture visual or audio data, reducing the risk of privacy violations typically associated with technologies like cameras or microphones. Its low-range nature also means that Zigbee-based systems are less likely to collect unintended data from outside the target area, making it a more privacy-friendly option for environments where privacy is a concern, such as hotel rooms or private homes. [65]

4.5.6. Risk of Detection Outside the Room

Zigbee signals are generally less prone to penetrate walls compared to technologies like Bluetooth or UWB, which reduces the risk of detecting individuals outside the designated area. Zigbee's limited range and signal strength make it ideal for contained environments, where detecting occupants in neighboring rooms or beyond the intended area is not desirable. This feature ensures that Zigbee-based systems can focus on the target area without the risk of cross-room detection, making it well-suited for applications where confined space monitoring is essential, such as in hotels or residential buildings. [63]

4.6. Sensor LiDAR

LiDAR (Light Detection and Ranging) is a technology that uses laser pulses to measure distances and create three-dimensional maps of an environment. It is highly effective in detecting and mapping the presence of objects or people. [66]

4.6.1. Detection Principles

LiDAR operates by emitting pulses of laser light, typically in the near-infrared spectrum, and measuring the time it takes for the light to bounce back from an object. By calculating the time of flight (ToF), the sensor determines the distance to the object, allowing it to generate 3D spatial data of the environment. [67] This data can then be used to create detailed three-dimensional models, making LiDAR an ideal choice for applications where precise detection and mapping are required, such as in autonomous vehicles or robotics. [68]

4.6.2. Accuracy and Robustness

LiDAR provides exceptional accuracy, often within millimeters, making it one of the most precise detection technologies available. This high level of accuracy is particularly beneficial for detecting and tracking human movements in complex environments, such as urban settings or indoor spaces. [67] However, environmental factors like fog, heavy rain, or dust can interfere with the laser pulses, reducing the accuracy of the system in adverse conditions. Despite these limitations, LiDAR remains highly robust in clear environments and can deliver reliable detection where other technologies might struggle. [67]

4.6.3. Scalability and Complexity

LiDAR systems are typically complex and expensive, limiting their scalability, especially for large-scale deployments. The high cost is not only associated with the hardware (sensors) but also the processing power required to manage and interpret the vast amounts of data generated by the system. [69] Due to these complexities, LiDAR is more commonly used in specialized applications like autonomous driving, industrial automation, or high-precision surveying, rather than in everyday or large-scale environments. While LiDAR can be integrated into large networks for broader coverage, the complexity and costs associated with installation and data processing make it less suitable for applications where cost efficiency is a priority. [69]

4.6.4. Cost and Installation Requirements

LiDAR sensors are expensive, but the need for powerful processing systems to handle the data further increases the overall cost of implementation. [70] This makes LiDAR a less viable option for environments where cost is a significant consideration, such as in residential or commercial settings. The installation of LiDAR systems also requires calibration and careful placement to ensure accurate data collection, especially in environments with obstacles or varying surfaces. Specialized technicians are often needed to install and maintain these systems, adding to the overall complexity and cost of deployment. [70]

4.6.5. Privacy Considerations

Unlike visual surveillance technologies such as cameras, LiDAR does not capture visual images or audio data, which significantly reduces privacy concerns. [71] Since LiDAR operates by measuring laser pulses, it only gathers spatial data about the environment, making it a non-invasive solution for detecting human presence without compromising personal privacy. This makes it ideal for use in settings where privacy is critical, such as healthcare facilities or private spaces. [71]

4.6.6. Risk of Detection Outside the Room

Since LiDAR does not rely on signals that penetrate walls, the risk of detecting individuals outside the intended area is minimized. The laser pulses used by LiDAR are generally absorbed or reflected by solid surfaces like walls, meaning that detection is confined to the area directly within the line of sight of the sensor. This feature makes LiDAR an ideal solution for focused detection in confined spaces, such as hotel rooms or indoor environments, where the detection of individuals outside the target area could present privacy concerns. [72]

4.7. Passive Infrared Sensors (PIR)

Passive Infrared (PIR) sensors detect infrared radiation emitted by objects, particularly from human bodies, by identifying temperature variations in the environment. [73] These sensors are highly effective in detecting human presence by recognizing small differences in infrared radiation between the human body and its surroundings. PIR sensors do not emit radiation; instead, they passively receive infrared waves, which makes them highly efficient for indoor applications.[73]

4.7.1. Detection Principles

PIR sensors work by detecting infrared radiation emitted by warm objects, such as humans. When an object with a temperature different from the ambient environment moves within the sensor's field of view, the PIR sensor registers this change in infrared radiation. [74] These sensors are most effective when there is a significant difference between the background temperature and the object being detected. [74]

4.7.2. Accuracy and Robustness

PIR sensors are generally accurate within their detection range, which typically covers around 10 meters. They are sensitive to movement and temperature changes, which allows for reliable detection of human presence in controlled environments. [74] However, their performance may be diminished in areas with rapidly changing temperatures or multiple heat sources, but they are well-suited for typical indoor environments where human movement is the primary detection goal. [74]

4.7.3. Scalability and Complexity

Due to their simplicity and ease of installation they can be integrated into a wide variety of smart home or building management systems with minimal effort, as they do not require complex calibration or extensive infrastructure. [75] Additionally, PIR sensors have low power consumption, which further simplifies their integration into battery-powered devices or energy-efficient systems. **yeonjin2021advances**

4.7.4. Cost and Installation Requirements

The low cost of PIR sensors makes them a popular choice for detecting human presence in a variety of settings. They are inexpensive to manufacture and purchase, and their installation is straightforward, requiring minimal technical knowledge. [76] PIR sensors can be easily integrated into existing electrical systems, making them a cost-effective solution for motion detection and automation.

4.7.5. Privacy Considerations

PIR sensors are considered non-invasive because they do not capture any personally identifiable information. Unlike technologies such as cameras or microphones, PIR sensors only detect infrared radiation, meaning they cannot record images or sounds. This makes them ideal for use in settings where privacy is a concern, such as hotel rooms or private homes. [73] The fact that they do not gather any visual or audio data further reduces privacy risks, making PIR sensors a safe option for maintaining privacy while ensuring human detection.

4.7.6. Risk of Detection Outside the Room

Since PIR sensors rely on infrared radiation emitted from objects within their immediate range, their detection capability is restricted to the room or space where they are installed, making them an ideal choice for room-specific detection applications. [73]

4.8. Ultrasonic Sensors

Ultrasonic sensors detect objects by emitting high-frequency sound waves and measuring the time it takes for the echo to return after bouncing off an object. **auptmann2002application** This method allows the sensor to determine the distance to the object based on the speed of sound in the environment. These sensors are widely used for proximity detection and are effective even in challenging conditions such as fog, dust, or in the presence of certain materials. [77]

4.8.1. Detection Principles

Ultrasonic sensors emit sound waves at frequencies above the human hearing range (typically between 20 kHz and 40 kHz), which reflect off objects. [78] By measuring the time of flight of the sound waves, the sensor calculates the distance to the object. This technology is particularly effective in environments where optical sensors may fail, such as in dusty or foggy conditions. Ultrasonic sensors are commonly used for human presence detection in applications like automated doors, parking sensors and robotics. [79]

4.8.2. Accuracy and Robustness

Ultrasonic sensors are generally very precise within their typical detection range of up to 5 meters, though this range can vary based on environmental conditions. [78] They are robust and perform reliably even in noisy environments, though extreme levels of sound interference can impact their accuracy. One key advantage of ultrasonic sensors is their ability to detect objects regardless of surface characteristics, which makes them highly effective in detecting human presence in a variety of conditions. [77] However, their accuracy may be reduced when detecting small or very soft objects, as these might not reflect sound waves as effectively. [79]

4.8.3. Scalability and Complexity

While ultrasonic sensors are relatively easy to implement on a small scale, they require more complex arrangements when deployed in large areas. To cover a larger space, multiple sensors need to be installed, which increases both the complexity and cost of the system. [80]

4.8.4. Cost and Installation Requirements

Ultrasonic sensors are generally affordable, especially for smaller installations, but the cost increases when many sensors are required to cover larger areas. Installation is typically straightforward, but in more complex setups, it may require careful calibration to avoid interference between sensors. **auptmann2002application**

4.8.5. Privacy Considerations

Ultrasonic sensors do not raise significant privacy concerns, as they do not capture personal data such as images or audio. These sensors operate by detecting the presence of objects through sound waves, making them an ideal solution for environments where privacy is a priority, such as hotel rooms or residential spaces. [81]

4.8.6. Risk of Detection Outside the Room

The risk of detecting individuals outside the designated area is low with ultrasonic sensors, as sound waves typically do not pass through solid surfaces like walls. [78] This feature ensures that detection remains focused on the intended space, minimizing the risk of false detections or interference from neighboring areas.

4.9. Radar

Radar technology operates by transmitting radio waves and measuring the reflected signals to detect objects, movement, and range. [82] Radar sensors are widely used for human presence detection due to their ability to detect even the smallest movements, such as breathing or subtle body shifts, they are also, highly versatile, allowing for detection in both line-of-sight and non-line-of-sight conditions. [83]

4.9.1. Detection Principles

Radar sensors emit radio waves that bounce off objects and return to the sensor. [82] The sensor then measures the time of flight and Doppler shift in the returning waves to calculate the distance, speed, and movement of the object. Unlike other detection technologies. Radar systems can operate in all weather conditions and are effective in low visibility environments such as fog or darkness. [84]

4.9.2. Accuracy and Robustness

Radar technology is known for its high accuracy and robustness, especially in environments where visual or infrared-based sensors might struggle. Radar can detect motion through walls, obstacles, and low-visibility conditions, making it highly reliable in complex environments. [84] However, signal interference from nearby devices operating in similar frequency bands can affect accuracy, although modern radar systems use techniques to mitigate interference. [85]

4.9.3. Scalability and Complexity

While radar systems are highly scalable, they tend to be more complex than other detection technologies due to the signal processing required to interpret the data. Deploying radar across large areas may require more sophisticated signal processing and networking systems, but their ability to function in non-line-of-sight environments makes them a versatile choice for both indoor and outdoor applications. [86]

4.9.4. Cost and Installation Requirements

The cost of radar technology varies depending on the resolution and range required. Higher-resolution radar sensors, which are capable of detecting fine movements like breathing, are generally more expensive due to the advanced signal processing needed. Installation also requires specialized expertise, as radar sensors must be calibrated to account for the environment and potential interference from other devices. [84]

4.9.5. Privacy Considerations

Radar sensors do not capture visual or audio data, making them less likely to raise privacy concerns compared to technologies like cameras. However, radar's ability to detect movement through walls can pose potential privacy risks, a proper configuration and calibration are essential to avoid unwanted detections outside the intended area. [87]

4.9.6. Risk of Detection Outside the Room

Due to its ability to penetrate walls and obstacles, radar sensors can detect movement in adjacent rooms or areas outside the intended detection zone if not properly configured, which could lead to false detection if not roper calibration. [87]

4.10. Comparative Table of Detection Technologies

A comparative table is drawn up with the above-mentioned bibliography and the data presented in the previous section.

As can be seen, within the parameters of comparison that were established at the time of evaluating each of the proposed technologies, the following ones are included:

- Network to be used, or rather, technology to be used.
- Detection principle, or principle of algorithm to be used, of those shown above, having some benefits or weaknesses depending on the situation.
- Precision, rather, in this section, is the accuracy with which it can detect an object within the area that seeks to find a person.
- Stability, it looks for the robustness that this type of technology has, and how complicated it is to use it, depending on the situation.
- Cost: Indicates what is the cost of implementing this type of technology, indicating if any of these is more expensive than another, having this type of item as a virtue or as something negative.

System	**Network**	**Accuracy and Robustness**	**Method**	**Scalability and Complexity**	**Cost and Requirements**	**Privacy**	**Detection Risk**	**Advantage**	**Disadvantage**
ToF (Time of Flight)	Infrared	Up to 1 mm	ToF	High, specialized sensors	Expensive, powerful processors	High	Low	A: High accuracy	D: Expensive.
Wi-Fi	WLAN	2.26m in 312 m^2	Triangulation	High, uses existing network	Low cost	Low	High	A: Reuses infrastructure	D: Low accuracy.
UWB	UWB	Tens of cm	TDoA and AoA	High, 3D coverage	Expensive, advanced infrastructure	Moderate	Low	A: High accuracy	D: High cost.
Zigbee	Zigbee	Meters	RSSI	High, moderate scalability	Low cost	Low	Medium	A: Scalable	D: Low accuracy.
Bluetooth	Bluetooth	1-10 meters	RSSI	High, very scalable	Low cost	Low	High	A: Compatible with mobile devices.	D: Low accuracy.
RFID	RFID	2-3 meters	TDoA	High, limited coverage	Low cost	High	Low	A: Unique object identification.	D: Requires extensive infrastructure components.
LiDAR Sensor	Laser	Millimeters to centimeters	ToF	High, specialized sensors	Expensive, requires advanced processing	High	Low	A: High 3D accuracy.	D: Very expensive and high complexity.

Table 1: Comparative Table of Detection Technologies

- Privacy: Important point in this report because with this is dismissed certain technologies or applications that are used for this situation, because to a large extent, it has that privacy for a hotel system is essential, because if it is not found with this type of situations, people can be annoyed by this point.
- As a point to summarize, we have the advantages and disadvantages for each technology, having a mini summary of each of these.

5. Analysis of Commercially Available Devices

In this section the study will focused in reviewing the current technologies, available in the market, taking into consideration product brief description, performance metrics, cost and installation/maintenance requirements.

5.1. Philips Hue Motion Sensor

It is a sensor designed for smart home automation, specifically to control the lighting of the Philips Hue system. It detects the presence of people using infrared radiation emitted by the human body, allowing lights to turn on automatically when someone enters a room and turn off when motion is no longer detected. It is compatible with systems such as Alexa, Google Assistant and Apple HomeKit, offering intelligent lighting control [88].

- **Performance Metrics** : Detects motion at a maximum distance of 5 meters, with a 100° angle. It is optimized for Philips Hue lights, with minimal turn-on latency [88].
- **Cost**: $39.99 USD.
- **Installation and Maintenance Requirements** Installation requirements: Simple installation with tape or screws. Operates on two AAA batteries, with a life of up to 2 years, requiring only battery replacement [88].

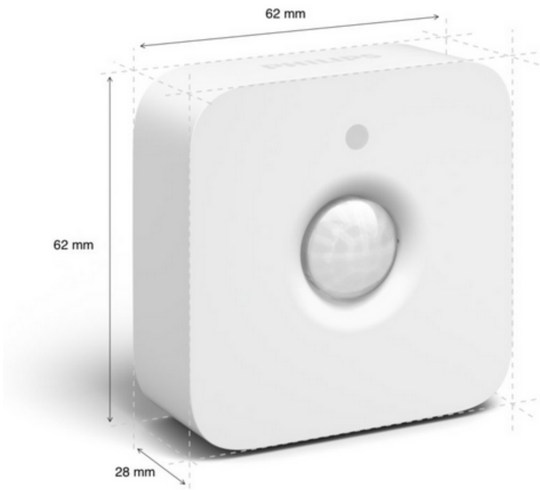

Fig. 6: Philips Hue Motion Sensor [88].

5.2. Ecolink Z-Wave Plus Motion Detector

It is a motion sensor that integrates with home automation systems using Z-Wave technology. Its passive infrared sensor detects changes in the thermal radiation of an environment to identify human presence. It is ideal for security systems and has a special mode to avoid false pet alarms. It can also be activated with other smart home devices to turn on lights or cameras. [89]

- **Performance Metrics** : It detects motion at a maximum distance of 5 meters, with an angle of 100°. It is optimized for Philips Hue lights, with minimum turn-on latency [89]
- **Cost**: $ 29.99 USD.

- **Installation and Maintenance Requirements** : Easy to install when paired with a Z-Wave hub. Powered by a CR123A lithium battery, with a battery life of up to 5 years [89]

5.3. Honeywell IS3050A

It is a dual-technology motion sensor that combines passive infrared (PIR) detection with ultrasound for increased accuracy. The combination of these technologies helps reduce false positives and improves detection capability even in complex conditions, such as drafty or hot areas. It is primarily used in advanced security systems. [90]

- **Performance Metrics** : Combination of passive infrared and ultrasound, with a detection range of up to 15 meters and a coverage angle of 90°. [90]
- **Price**: $ 79.99 USD.
- **Installation and Maintenance Requirements** : Requires professional installation in many cases, due to the combination of technologies. Low maintenance once properly installed. [90]

Fig. 7: Honeywell IS3050A [90]

5.4. Aqara Human Presence Sensor FP1

It is a device which uses radar technology to detect human presence in a room, even in situations where there is minimal movement, such as when a person is sitting or breathing. This sensor is ideal for home automation applications, as it can control lighting, heating and other devices based on room occupancy. It is especially useful in spaces where continuous sensing is desired without the need for constant motion. [91]

- **Performance Metrics**: Uses 60 GHz radar technology, capable of detecting the presence of people without motion, even through thin walls. Detection range up to 5 meters [91].
- **Price**: $ 99.99 USD.
- **Installation and Maintenance Requirements**: Easy installation on ceilings or walls. Powered by a USB-C cable, eliminating the need to change batteries. [91]

5.5. Nest Cam IQ Indoor

It is a smart security camera designed for the home, with facial recognition capability. It uses artificial vision algorithms to identify people and differentiate between humans, pets or moving objects. It offers high-definition video and personalized notifications that alert the user about activity in their home. This camera is part of the Google Nest ecosystem and integrates seamlessly with other smart devices [92]

- **Performance Metrics**: Camera with facial recognition, 1080p resolution and 12x digital zoom. Detects people and sends real-time alerts to the Google Home app. Only detects people who are in the line of sight of the device, as it analyzes faces and figures by itself. [92]
- **Cost**: $ 299 USD.
- **Installation and maintance requerimients**: Easy to install and configure using the Google Home app. Requires constant connection to power and internet. Minimal maintenance, with automatic firmware updates. [92]

Fig. 8: Nest Cam IQ Indoor [92].

5.6. Smartmat

It is a mat equipped with pressure sensors that detect the presence of people when they stand or sit on it. It is designed for applications in smart homes, such as device control, or in healthcare environments, to monitor the activity of elderly people. Although its technology is relatively simple, its application is versatile in automation and healthcare systems. [93]

- **Performance Metrics**: Pressure sensor that detects when a person sits or stands on it. It could be used to indicate when the guest enters and leaves the room, because as it is a pressure sensor, the mat will indicate if it was pressed for a certain time [93] .
- **Cost**: $ 149 USD.
- **Installation and maintance requerimients**: Easy to install (just place it on the floor). Does not require regular maintenance, it is only necessary to check the condition of the device [93] .

5.7. Velodyne LiDAR VLP-16

Also known as Puck, it is a compact LiDAR sensor used primarily in autonomous vehicles and robotics to map 3D environments. However, it is also used in advanced security systems to detect the presence of people in a space by analyzing distances and shapes. This technology is extremely accurate, even in dark or low visibility environments [94].

- **Performance Metrics**: LiDAR sensor maps 3D environments with a range of up to 100 meters and an acquisition rate of 300,000 points per second (Ouster,n.d).
- **Cost**: $ 3999 USD.
- **Installation and maintance requerimients**: Requires professional installation and specialized software to interpret the data. Maintenance includes periodic calibration and cleaning of the optical sensors [94].

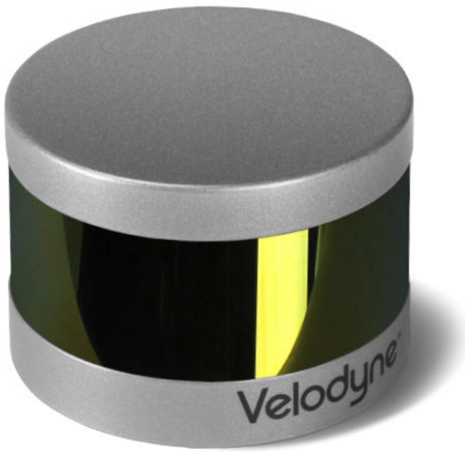

Fig. 9: Velodyne Lida VLP-16 [94].

6. Case Study: Hotel Room Implementation

6.1. Selected Sensor

For the development of this thesis, the P-NUCLEO-53L7A1 was used, this VL53L7CX STM32 Nucleo pack with X-NUCLEO-53L7A1 expansion board and NUCLEO-F401RE development board, it conforms a complete evaluation kit that allows to learn, evaluate, and develop applications using the VL53L7CX Time-of-Flight 8x8 multizone ranging sensor with 90° FoV. [95]

Fig. 10: P-NUCLEO-53L7A1, Evaluation Kit. [95]

The X-NUCLEO-53L7A1 of the kit, is an expansion board for any STM32 Nucleo board. It allows the user to test the VL53L7CX sensor functionality, to program it and to understand how to develop an application using this sensor. This expansion board integrates the VL53L7CX sensor, Arduino UNO R3 connectors and connectors for SATEL-VL53L7CX optional breakout boards. [95]

Fig. 11: X-NUCLEO-53L7A1, Expansion Board. [95]

The kit also includes a NUCLEO-F401RE development board, this STM32 Nucleo-64 board provides an affordable and flexible way for users to try out new concepts and build prototypes by choosing from the various combinations of performance and power consumption features provided by the STM32 microcontroller. [95]

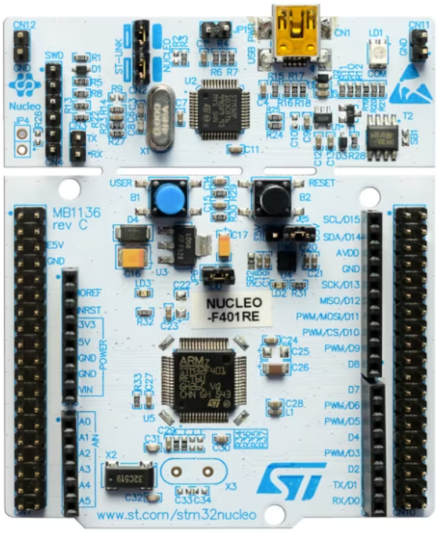

Fig. 12: NUCLEO-F401RE, Development Board. [95]

This evaluation kit was chosen considering: [95]

- The VL53L7CX Time-of-Flight sensor offers a 90° diagonal FoV, specifically designed for applications that require an ultrawide FoV.
- Based on ST FlightSense technology, the sensor incorporates an efficient metasurface lens (DOE - Diffractive Optical Element) placed on the laser emitter, enabling the projection of a 60° x 60° square FoV onto the scene.
- Its multizone capability provides a matrix of 8x8 zones (64 zones) and can work at fast speeds (60 Hz) up to 350 cm.
- ST patented algorithms and innovative module construction allow the VL53L7CX to detect, in each zone, multiple objects within the FoV with depth understanding.
- Like all Time-of-Flight (ToF) sensors based on ST FlightSense technology, the VL53L7CX records, in each zone, an absolute distance regardless of the target color and reflectance.

These features make the sensor optimal for detecting people inside a hotel room.

6.2. Installation and Configuration

In order to detect the presence of people in hotel rooms and save energy when empty, tests were carried out in an apartment with characteristics similar to those of a hotel room. And to facilitate both, installation and correct location, the P-NUCLEO-53L7A1 evaluation kit was adapted to a box, which allowed proper positioning.

A webcam was integrated into the same box, whose function is to verify the accuracy of the sensor measurements. By sharing the same field of view, the camera will confirm that the data is consistent and matches what is happening in the room. Figure 13 shows the sensor configuration, previously described.

Fig. 13: Sensor Configuration.

The sensor was installed in the center of the ceiling, as seen in the Figure 14, ensuring that its detection field covered the access to the room, since people must always pass through there, either to enter or leave. This is a strategic point, as generally in this area there is also the coat rack where jackets and keys are placed, as well as the shoe rack where people leave their shoes before entering. In addition, the sensor also covers the access door to the bathroom, which allows collecting a greater amount of data to detect the presence of people.

Fig. 14: Sensor Location.

6.3. Data Collection

Once the sensor was located at the ceiling of the room, data acquisition was carried out using the STSW-IMG048 software developed by STMicroelectronics.[37] This software is a Complete turnkey solution for Smart Presence Detection (SPD) with advanced algorithms using time-of-flight (ToF) sensors, that uses motion detection to accurately detect the presence and position of people. [95]

The advanced algorithms offer five features to enhance system efficiency and the user experience. Unlike standard ToF sensors that do not include advanced algorithms, ST's SPD solution is able to track a person's position, filter passing-by movement, wake the system up when someone steps in front of the device, and distinguish immobile humans from objects. [95]

Using a turnkey solution based on FlightSense technology provides full privacy as it uses ST's ToF sensors to compute distance information without the need for a camera module. The solution's performance is not affected by target reflectance, making it suitable for use in low light conditions. [95]

The sensor has a motion detector feature embedded in its firmware and can differentiate a human from an object. Moving objects wake up the system, which analyzes and decides if this is an object or a human. [95]

The procedure for acquiring data with the software is described step by step below:

Firstly, connect the board via a USB to Micro-USB cable and the webcam via a USB cable to the PC. Then, open the *FW* folder in the Smart Presence Detection EVK repository to find the firmware compatible with the VL53L7CX sensor. [95]

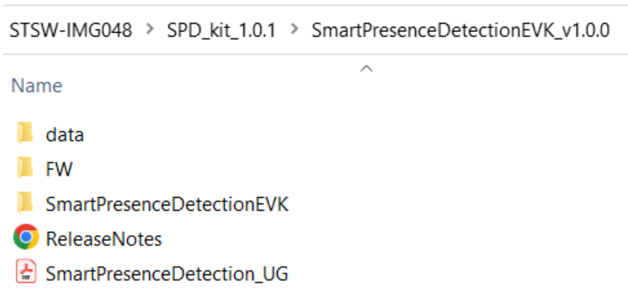

Fig. 15: Firmware Folder.

Subsequently, drag and drop the *.bin* file to flash the board.

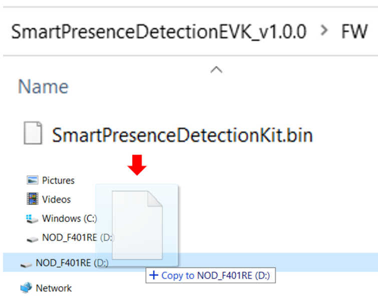

Fig. 16: Smart Presence Detection Firmware.

To launch the *Smart Presence Detection EVK GUI* software, Double-click on the *.exe* file in the SmartPresenceDetectionEVK folder.

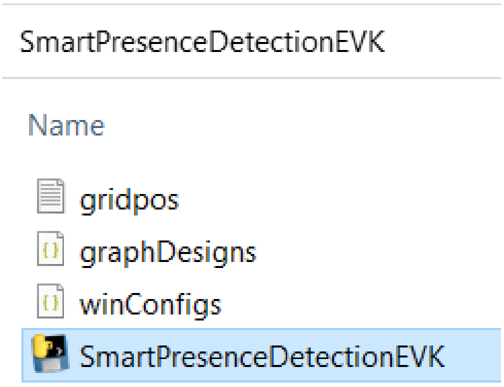

Fig. 17: Smart Presence Detection EVK GUI.

It is necessary to ensure that:

- The board is automatically detected and selected. If not, the *Com port* list should be refreshed and then select a board flashed with the firmware.
- Select the sensor driver: SmartPresenceDetection VL53L7
- Select the preset: 8x8.

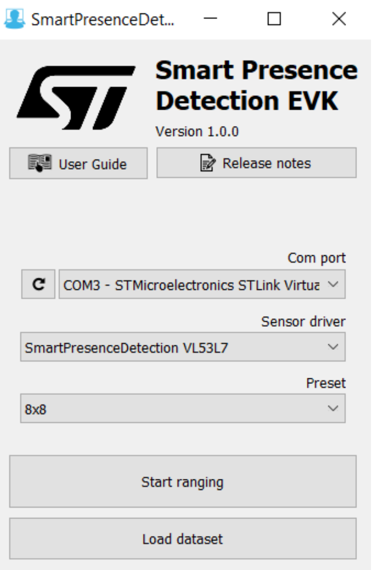

Fig. 18: Smart Presence Detection GUI Configuration.

Once the above is set up, click on *Start ranging* to start the measurement with the sensor. A window, similar to the one in Figure 19 will launch, in which the sensor's field can be observed divided into 64 zones (8x8), and in each of them, a number corresponding to the distance at which the objects are located in this same field.

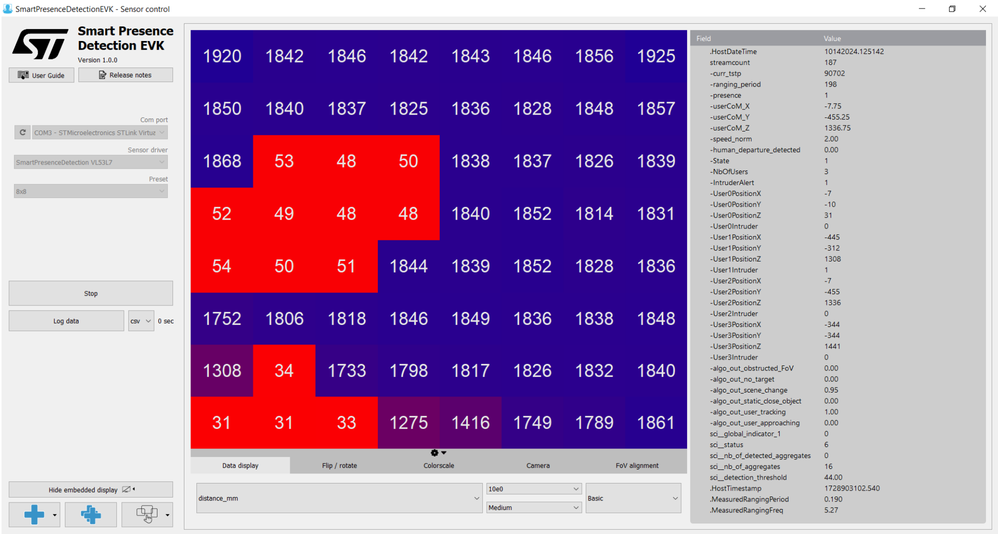

Fig. 19: Smart Presence Detection EVK Interface.

To display the live webcam feed, click on *Display camera* and the camera image should appear, if it does not occur, make sure that the webcam is functional. When several webcams are connected to the laptop, it is necessary to change the *Camera id* until get the desired camera image.

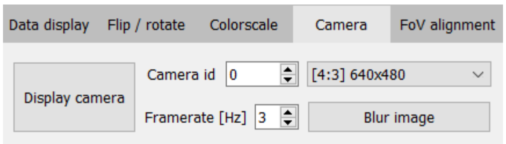

Fig. 20: Webcam Configuration.

After this configuration, the interface should look like Figure 21, with the camera image overlapping and merging with the sensor's distance measurements.

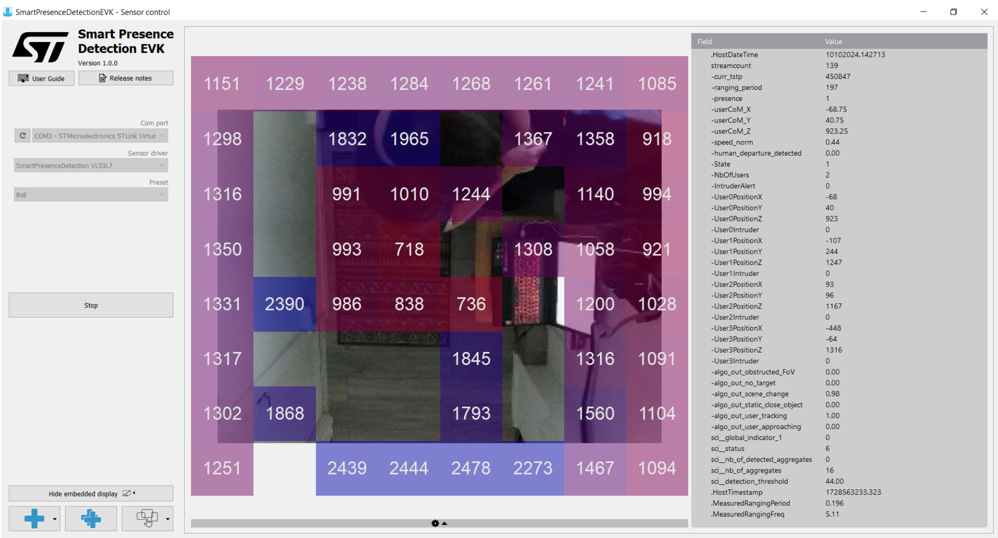

Fig. 21: Smart Presence Detection EVK Interface and Webcam Image.

To start data logging (recording), the file format must be selected and then click on the *Log data* button, after that the button should turn blue.

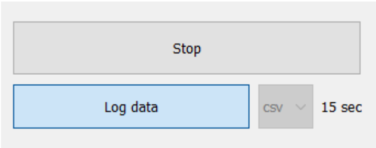

Fig. 22: Log Data Configuration.

Once data logging has started, a sequence of tests are performed in order to verify the operation of the sensor, these will be described in the following section. And, when the tests are finished, click again on the *Log data* button to stop data logging.

The acquired data is stored in the folder *data*, located in the same folder where the software is, here a new folder will be created whose name contains the date and time of capture, as can be seen in Figure 23.

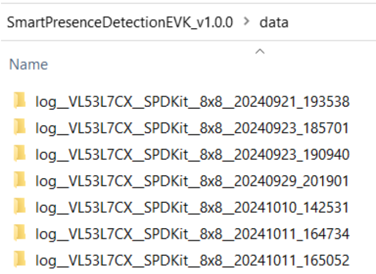

Fig. 23: Data Folder.

Using Smart Presence Detection EVK logger allows to monitor, log and replay all Smart Presence Detection algorithm internal variables.

In order to view the acquired data, open the software and click on *Load dataset* (Figure 24), and select the folder of the previously saved data (Figure 23).

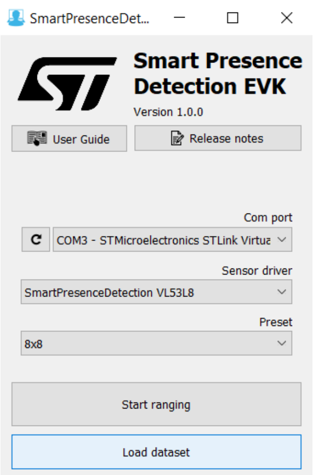

Fig. 24: Load Dataset Configuration.

Finally, an interface like the one in Figure 25 will open where you can see the data acquired in the tests performed.

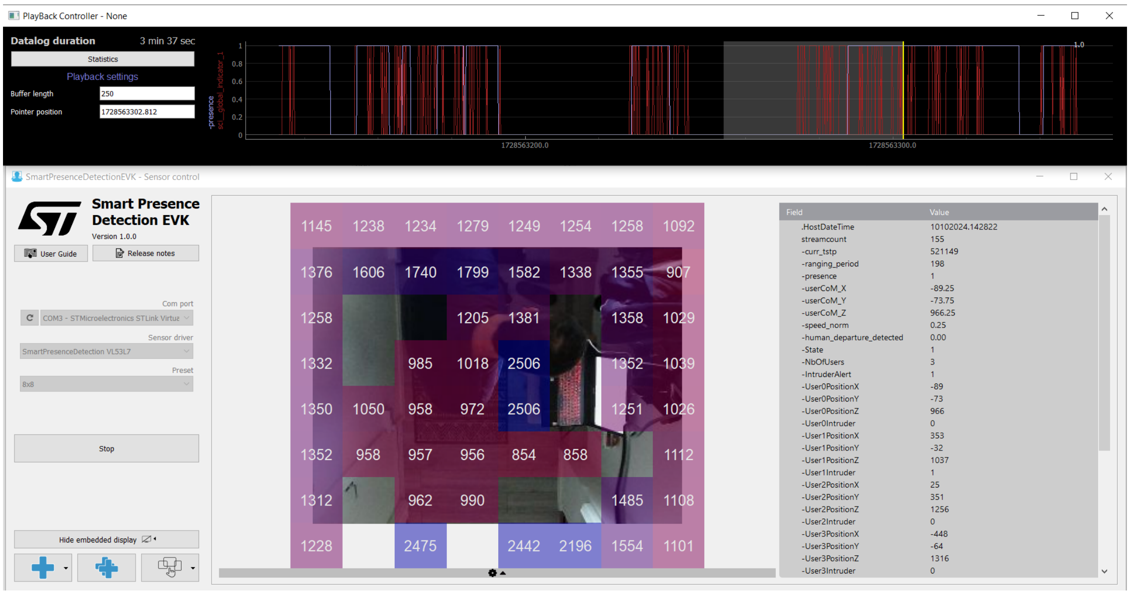

Fig. 25: Loaded Dataset Interface.

Thanks to numerous features (2D display over camera frame, curve plotting, SPD widget...), Smart Presence Detection EVK allows for deep analysis of any data from the the ST ToF sensor and all parameters of the Smart Presence Detection algorithm. [95]

6.4. Performance Evaluation

The primary objective of these tests was to evaluate the potential effectiveness and accuracy of the VL53L7CX sensor in detecting the presence of people in a simulated hotel room environment. The tests aimed to observe the sensor's capability to identify human presence and differentiate between human and non-human objects. Additionally, the tests sought to assess the sensor's integration with the camera feed to ensure consistent data collection and qualitative validation.

The main intention of these tests was to establish whether the VL53L7CX sensor has any potential efficacy or accuracy in detecting the presence of people in an understudy simulated hotel room. The tests intended to evaluate the ability of the sensor to detect human presence and the capacity to distinguish between human substance and other types of objects. In addition, the tests aimed at evaluating the sensor's incorporation with the camera feed for consistency of data collection and qualitative confirmation.

6.4.1. Test Environment and Conditions

The tests were conducted in an apartment that closely simulated the layout of a typical hotel room. The environment included common elements that can be found at the entrance of a hotel room, allowing for realistic human interaction with the space. The sensor was installed on the ceiling in a central location, covering key areas such as the room entrance, bathroom door, and the space around the coat rack and shoe rack. The following conditions were varied during testing to mimic real-world scenarios:

- **Lighting**: The tests were performed under different lighting conditions, including bright light, dim light, and complete darkness, to qualitatively assess how lighting might influence the sensor's performance.
- **Movement**: Both static and dynamic movements were introduced to observe the sensor's response to people standing still versus those walking in and out of the room. Movements were also recorded at varying distances from the sensor.

6.4.2. Test Criteria

The criteria for evaluating the sensor's performance were based on qualitative observations:

- **Detection Accuracy**: The sensor's ability to detect the presence of a person was compared visually with the camera feed.
- **Speed of Detection**: Although exact measurement of detection speed was not recorded, the general responsiveness of the sensor was observed.
- **False Positives/Negatives**: Instances of the sensor mistakenly identifying human presence (false positives) or failing to detect it when a person was present (false negatives) were noted.
- **Distance Accuracy**: The sensor's precision in estimating the distance of objects and people was qualitatively assessed based on visual analysis.

6.4.3. Test Description and Results

The tests were designed to simulate typical scenarios of people entering, moving within, and leaving a hotel room. The sensor's responses were compared with the images captured by the integrated webcam to ensure consistency. By positioning the camera to share the same field of view as the sensor, we ensured that the visual data could be compared directly with the sensor's measurements to verify the accuracy of the detection process.

The test scenario was based on a typical sequence of actions a person might take upon entering a hotel room:

1. **Entering the Room**: The door opens, and a person enters the room. Upon entering, the person removes their jacket and places it on the coat rack, then proceeds to take off their shoes.

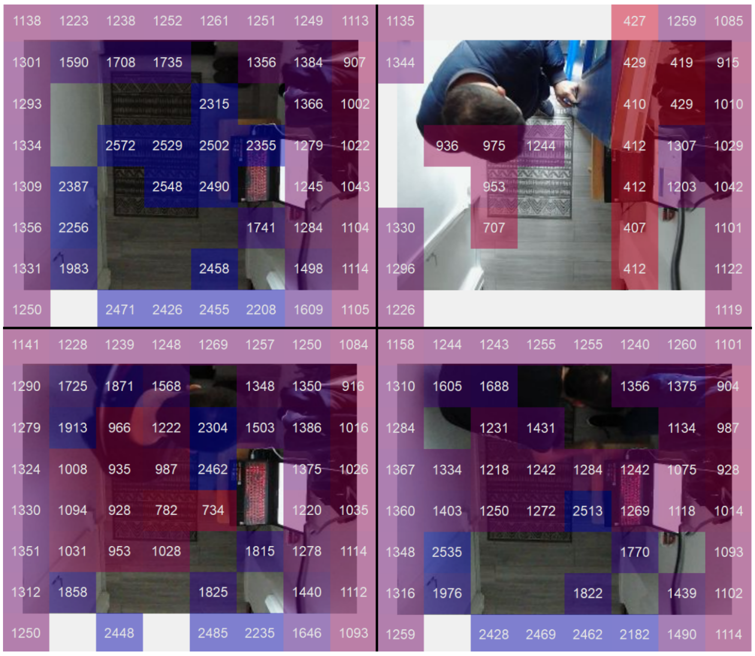

Fig. 26: Results Entering the Room.

2. **Movement Within the Room**: After removing the shoes and jacket, the person leaves the sensor's field of view by entering the bathroom. This tests whether the sensor accurately detects when the person is no longer in the primary zone.

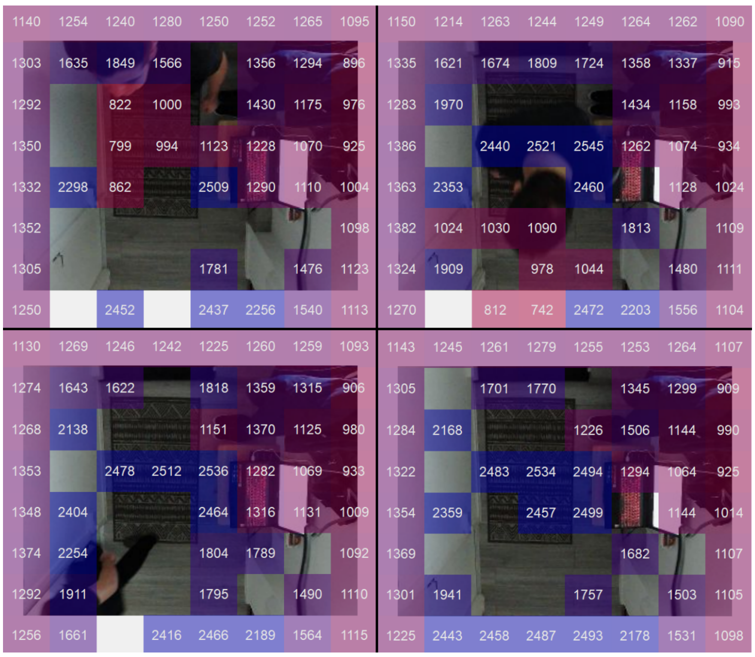

Fig. 27: Results Entering the Bathroom.

3. **Re-entering the Sensor's View**: After exiting the bathroom, the person retrieves an item from their jacket and then moves towards the far end of the room, potentially

where the bed is located, which is outside the sensor's range. This step tests the sensor's ability to distinguish between brief absences and longer ones.

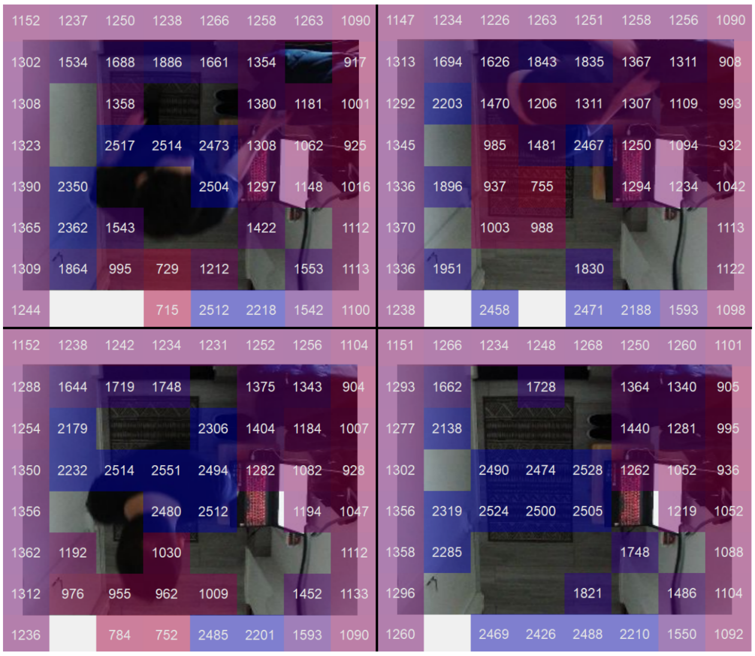

Fig. 28: Results Re-entering the Sensor's View.

4. **Preparing to Leave**: The person returns to the coat rack, puts on the jacket, then the shoes, and prepares to leave the room.

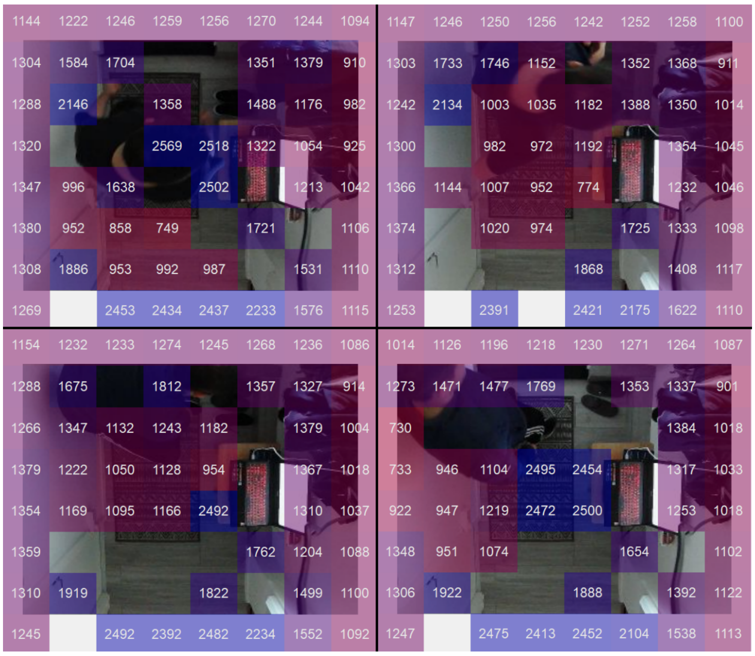

Fig. 29: Results Preparing to Leave.

Finally, they exit, testing the sensor's ability to detect when the room becomes empty.

Fig. 30: Results Leaving the Room.

During these tests, the VL53L7CX sensor's 8x8 multizone matrix effectively tracked the individual's movements, as can be seen in Figures 26, 27, 28, 29 and 30. Blue boxes are observed when the distance is greater, and red boxes when the distance is shorter, these data vary throughout the tests, and it is possible to observe that the sensor accurately identified when the person entered or exited its field of view, with specific stages clearly reflected in the data.

Real-time data logging from the sensor was consistently aligned with the visual evidence captured by the camera. Each movement and interaction with the room was mirrored in the sensor's data, confirming its ability to detect changes accurately.

Key Observations:

- The sensor successfully detected the individual's movement at the entrance upon entering the room.
- It registered specific actions like the removal of the jacket and the placement of shoes by tracking variations in the distance within the relevant zones.
- When the person exited to the bathroom, the sensor correctly noted the departure from its detection area.
- On returning to the coat rack, the sensor resumed tracking the activity, and ultimately recorded the room as unoccupied when the person left.

These observations demonstrated the sensor's capability to accurately detect both presence and movement within the room's key areas, including the entrance, coat rack, and bathroom. The synchronization with the camera feed was crucial in verifying the sensor's real-time responsiveness and precision.

7. Discussion of Results

7.1. Summary of Findings

The research conducted on various detection technologies has revealed their significant potential for improving energy efficiency in hotel environments. A wide range of sensors, including Time of Flight (ToF), WiFi, UWB, Bluetooth, RFID, Zigbee, LiDAR, PIR, Ultrasonic and Radar, have been comparated for their capabilities in detecting human presence in confined spaces, taking into account characteristics such as accuracy and robustness, scalability and complexity, cost and instillation requirements, privacy considerations and risk of detection outside the room.

Taking into account the systematic literature review, it is possible to affirm that the VL53L7CX Time of Flight sensor stands out as an appropriate solution for indoor presence detection, especially in hotel rooms, for various reasons:

- **Cost-Effectiveness**: The VL53L7CX has been found to deliver suitable, now dependent performance for the price. Its cost is advantageous as it allows for mass production in the hotel industry, which is necessary for most large-scale implementations while managing cost considerations.
- **Ease of Installation and Integration**: Since the sensor is small and easy to install, it can be placed in multiple locations inside a room, for instance, on the ceiling and walls. This positioning also helps to enhance coverage without the need for extensive structural changes or prolonged installation time, thus saving both installation and upkeep costs.
- **Privacy Protection**: One of the most beneficial factors of the VL53L7CX sensor is its ability to detect human presence without capturing identifiable personal data, such as pictures or recordings. Unlike cameras, ToF sensors provide a high level of privacy for guests which the hospitality industry requires.
- **Energy Efficiency**: The VL53L7CX is designed to operate with low power consumption, thus making it ideal for applications such as smart hotel room management systems where energy consumption is critical. The sensor makes it easier to manage energy efficiency within the room because it can efficiently monitor the presence of people, thereby intelligently managing lighting, heating and cooling of the room when necessary.
- **Reduced Risk of Detection Errors Outside the Room**: The range and detection capability of the VL53L7CX are well-suited for confined spaces. It is set up in such a way that it harbors an interest in the target region of a room decreasing the chances of detecting movement or presence in the outer regions of the primary focus area. This accuracy minimizes the chances of unwanted system activation due to movement detection of other rooms hence increasing the performance of the sensor in relation to occupancy-based automation.
- **Adaptability to Various Lighting Conditions**: As per the manufacturer's information, the performance of the sensor is reported to be significantly autonomous from

the lighting conditions that the sensor is exposed to including instances when there is no light available at all. This wide operational range enhances the effectiveness of the sensor allowing it to work at any time without having to worry about light level adjustment due.

- **Minimization of False Positives/Negatives**: While the VL53L7CX sensor reacts to motion, its algorithms are also able to differentiate between humans and non-human elements at their initial stage of detection. This minimizes false positives as when non-moving objects intrude their visual scope. On the contrary, even though the sensor may fail to detect individuals who have sat still for an extended time, the most trivial motion sets up a quick review in response, so the sensor works well to changes.
- **Scalability and Versatility**: This potential of the sensor to interact with other technologies for room management such as the HVAC (Heating, Ventilation, and Air Conditioning) and lighting makes it a scalable solution. It is easy for hotels to apply it for several rooms or up to an entire floor since it will allow centralized control and supervision.

On the other hand, the results observed from the tests are analyzed as follows:

- **Detection Accuracy**: The VL53L7CX sensor generally demonstrated good accuracy in detecting human presence under various conditions, with a noticeable improvement in low-light environments. These observations align with the manufacturer's claim that the sensor's performance is not significantly affected by lighting conditions but may be influenced by the reflectance of objects in the environment. In bright lighting scenarios, a slight decrease in precision was observed, likely due to reflections or other optical interferences. It is important to note that these findings are based on qualitative analysis, as no quantitative data was collected.
- **Speed of Detection**: The sensor appeared to respond promptly to movements, but without precise timing measurements, we cannot definitively state its exact detection speed. The observed response seemed reasonably quick across different lighting conditions, supporting its capability for real-time presence detection.
- **False Positives/Negatives**: During the tests, false positives were noted primarily when non-human objects, such as moving coats or bags, entered the sensor's field of view. However, once these objects stopped moving, the software's built-in algorithms effectively recognized that they were not humans, thereby minimizing the occurrence of sustained false positives. This highlights the sensor's capability to correct initial mistakes by continuously analyzing the scene.

  False negatives were primarily observed when a person remained completely still for an extended period. Since the software relies on motion to detect presence, the sensor could temporarily lose track of a person who was motionless. However, as soon as any movement was detected, the software reanalyzed the situation and accurately marked the presence of the individual. This behavior suggests that while the sensor is highly sensitive to movement, its ability to detect stationary individuals could be further improved.

- **Distance Accuracy**: The sensor seemed to provide reasonably accurate distance measurements, especially in the central zones of its field of view. However, since no exact distance values were recorded, we cannot definitively quantify its precision. There was a slight perceived reduction in accuracy at the edges of the field, but this did not significantly impact its overall performance in detecting presence.

Finally, the commercially available indoor presence detection devices are convenient as they are ready to use; however, a custom device built with the use of the VL53L7CX sensor is superior in many respects such as: privacy, effectiveness, versatility, and energy usage. The limitation of the power consumption and the emphasis on the privacy positively make the VL53L7CX sensor fit for environments like hotel rooms where guest experience as well as the efficiency of the operations is important. Moreover, the versatility and affordability of this sensor open the doors for development of custom solutions which will be more efficient than typical solutions available on the market whenever accurate and dependable presence detection is more so required.

7.2. Challenges and Trade-offs

While the benefits of these technologies are clear, several challenges and trade-offs must be considered.

Speaking specifically about the VL53L7CX sensor, in addition to its dependency on motion for detecting presence, its precision under high-light conditions was also noted as a challenge. Reflections from brightly lit objects and surfaces affected the sensor's ability to consistently and accurately identify human presence, leading to minor reductions in detection accuracy. Balancing the trade-off between sensitivity to light conditions and maintaining robust presence detection remains a crucial area for development. Optimizing the sensor's performance to ensure it functions effectively regardless of ambient lighting levels is an important consideration for its application in dynamic hotel room environments.

Aditionally, cost remains a barrier for many hotels, particularly smaller establishments. Although ToF and thermal imaging technologies offer enhanced performance, their initial investment may deter some operators. However, the long-term energy savings can often offset these costs, leading to improved operational efficiency over time.

7.3. Opportunities for Future Research

Future research should focus on developing advanced algorithms that enhance the performance of these technologies in complex environments. For instance, refining the signal processing capabilities of ToF sensors could minimize the impact of environmental factors, such as reflective surfaces or ambient temperature variation.

There is also significant potential for integrating different detection technologies into a unified system. Combining ToF sensors with RF or UWB technologies could allow for greater flexibility and adaptability in occupancy detection, particularly in areas where walls and obstacles impede direct sensor lines. This integration could lead to more robust energy management systems in hotels, allowing for real-time adjustments based on accurate occupancy data.

Additionally, optimizing the energy consumption of sensors themselves is crucial. Research into more efficient sensor designs could further enhance sustainability efforts within the hospitality industry, ensuring that the deployment of multiple sensors across a property remains viable from both an economic and environmental perspective.

For the VL53L7CX sensor the future research could focus on two primary areas of improvement:

Further analysis should be conducted to understand how the sensor performs under different lighting conditions, ranging from complete darkness to bright light, and in situations where multiple people are present. This will help evaluate the sensor's capability to handle complex real-world environments, where lighting and the number of occupants can significantly influence performance.

A detailed quantitative analysis is essential to draw more definitive conclusions about the sensor's effectiveness. Key variables that should be measured include detection accuracy, speed of detection, false positive and negative rates, distance accuracy, and the impact of varying light conditions on sensor reliability. Collecting numerical data on these aspects would provide a more robust evaluation and help identify specific areas for technological enhancement.

8. Conclusion

8.1. Implications for the Hotel Industry

The implications of these findings for the hotel industry are substantial. The adoption of advanced detection technologies can lead to significant operational cost reductions and sustainability improvements. As hotels are increasingly pressured to minimize their environmental impact, solutions such as ToF provide practical means to manage energy consumption without sacrificing guest comfort.

By automating energy systems like lighting and HVAC based on real-time occupancy data, hotels can lower their energy bills and contribute to reducing overall carbon emissions. The implementation of these technologies not only supports energy efficiency but also aligns with the growing consumer preference for environmentally friendly practices in the hospitality sector.

In conclusion, while challenges related to cost, accuracy, and environmental factors persist, the potential benefits of integrating these diverse detection technologies in the hotel industry are significant. Continued advancements in sensor technology and strategic implementation can pave the way for enhanced energy efficiency and sustainability in the hospitality sector.

8.2. Summary of Contributions

The study's key takeaway is that while various sensor technologies provide specific benefits, the VL53L7CX ToF sensor offers a comprehensive solution that balances accuracy, privacy, and energy efficiency. Its deployment in hotel environments presents a clear path forward for the industry to address both sustainability and operational efficiency.

Taking into account the tests performed with the VL53L7CX sensor, several important contributions to understand the presence detection using ToF sensors were obtained, such as:

The VL53L7CX sensor's ability to detect presence accurately under a variety of conditions was demonstrated, including low-light environments, validating the manufacturer's claims through real-world tests.

Valuable insights into how the sensor's software effectively reduces false positives by re-evaluating stationary objects were provided, as well as the challenge it faces in detecting motionless individuals.

It should be noted that while the sensor's performance is generally independent of light conditions, high-light scenarios could lead to slight inaccuracies due to reflecting, suggesting areas for algorithmic improvement to mitigate this issue.

It could be stated that the VL53L7CX sensor is a viable and cost efficient solution owing to its ease of operation, low power consumption, adaptability in the environments, and privacy features. Thanks to these traits, it is possible for hotels to provide energy efficient and smart designed rooms for their guests without any sacrifice on guest privacy and efficiency of the operations.

8.3. Recommendations

Given the findings, it is recommended that hotels prioritize the adoption of non-invasive sensors as a cornerstone of their energy management strategy. These sensors can deliver significant energy savings, primarily by reducing the operational load of lighting and HVAC systems when rooms are unoccupied.

Taking into account the tests carried out with the sensor, the recommendations are:

Algorithmic Enhancements: Develop and implement algorithms that improve detection of stationary individuals by recognizing subtle movements or physiological signals like breathing.

Reflectance Optimization: Address the sensor's susceptibility to reflectance issues in brightly lit conditions through advanced filtering techniques or calibration adjustments.

Comprehensive Quantitative Data Collection: Prioritize the collection of quantitative data on key variables like detection speed, accuracy, false positive/negative rates, and the impact of lighting to facilitate more precise assessments of the sensor's capabilities.

Strategic Sensor Deployment: Utilize strategic positioning of sensors in high-activity areas to maximize detection efficiency while minimizing the influence of peripheral disturbances.

8.4. Final Considerations

The results of the testing and analysis conducted with the VL53L7CX sensor highlight its potential as a valuable tool for presence detection in hotel room environments. The sensor exhibited a generally reliable ability to detect human presence and track movement. Its integration with camera feeds provided a qualitative validation of its performance, demonstrating its capability for real-time occupancy detection. However, this study has also uncovered areas where the sensor's functionality could be refined and optimized.

To conclude, while the sensor has demonstrated a solid foundation for practical application in the hospitality industry, continued refinement and rigorous testing will be vital in enhancing its reliability and accuracy. Leveraging these insights will not only improve the sensor's integration into hotel automation systems but also contribute to broader efforts in developing energy-efficient and intelligent solutions for the smart building industry. The lessons learned from this work provide a valuable framework for future innovations, driving forward the adoption of technology that supports sustainable and efficient energy use in modern facilities.

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