Chapter 6

Advanced Sensing and Automation Technologies

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In the context of social distancing, various sensing and automation technologies can bring key roles in providing intelligent social distancing scenarios. In this chapter, we present overviews and state-of-the-art applications of emerging sensing and automation technologies including ultrasound, inertial sensor, visible light, and thermal. These four technologies can provide small-to-large coverage, sufficiently low deployment and operational costs, and high accuracy as well as privacy for indoor and/or outdoor environments. Specifically, ultrasound technology that leverages periodical ultrasonic beacons (UBs) can be utilized to keep distance among people, real-time monitoring in public buildings, and mobile robot navigation in indoor environments. Inertial sensor technology, which contains gyroscope and accelerometer, is useful to recognize positions of pedestrians for keeping distance and perform automation using autonomous vehicles, e.g., medical robots and unmanned aerial vehicles (UAVs). The use of visible light coming from the light-emitting diodes (LEDs) can also provide low-cost crowd monitoring system as well as navigation assistance system in a large-scale indoor area, and smart traffic control among vehicles on the roads. In a low-light condition, thermal-based system using infrared and imaging camera can be used to control distance among people, physical contact tracing, and real-time traffic monitoring over long distance. To this end, each emerging sensing/automation technology has unique features that are expected to be the potential solution for specific social distancing scenarios. In the following sections, we discuss the aforementioned sensing/automation technologies and their scenarios for social distancing applications in more detail.

1.1 Ultrasound

Ultrasound communication, especially ultrasonic positioning system (UPS), has been commonly used for indoor positioning application thanks to its short coverage and

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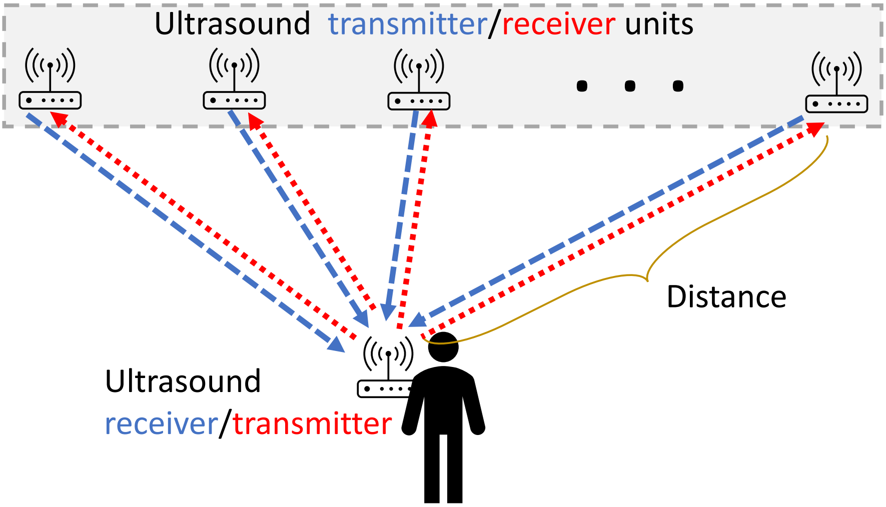


Figure 1.1 A general ultrasound system for positioning application.

high accuracy of centimeters [1]. Different from the frequency range of normal human hearing, i.e., between 20Hz and 20kHz, ultrasound operates with the frequency higher than 20kHz, e.g., UPS with 40kHz. Specifically, as shown in Figure 1.1, the UPS may contain ultrasound beacons (UBs) which work as tags or nodes to transmit ultrasound signals of the target users (red dotted lines) or the array of sensing nodes on the walls or ceiling (blue dotted lines) for further processing. These UBs will broadcast the analog ultrasound and radio frequency (RF) signals periodically and simultaneously using their information, e.g., unique IDs and current timestamp. Leveraging the ultrasound and RF signals, the position of target users can be calculated using positioning techniques, e.g., *trilateration* or *triangulation* mechanism [2], upon passing through analog-to-digital converter and a digital signal processor.

Compared with other RF-based positioning methods, ultrasound has some benefits. In particular, ultrasound does not need a line-of-sight between the ultrasound transmitter and ultrasound receiver. Additionally, it does not interfere with electromagnetic waves when the ultrasound signals are transmitted. However, due to its limited ultrasound signal propagation, ultrasound is only effective to be used for social distancing scenarios in indoor environments. In the following, we provide several social distancing scenarios including distance among people, real-time crowd monitoring, and automation, that can be implemented using ultrasound devices.

1.1.1 Distance Among People

In this scenario, UPS can be utilized to notify people when their positions are too close from each other using Active Bat and Cricket systems.

Active Bat-based UPS

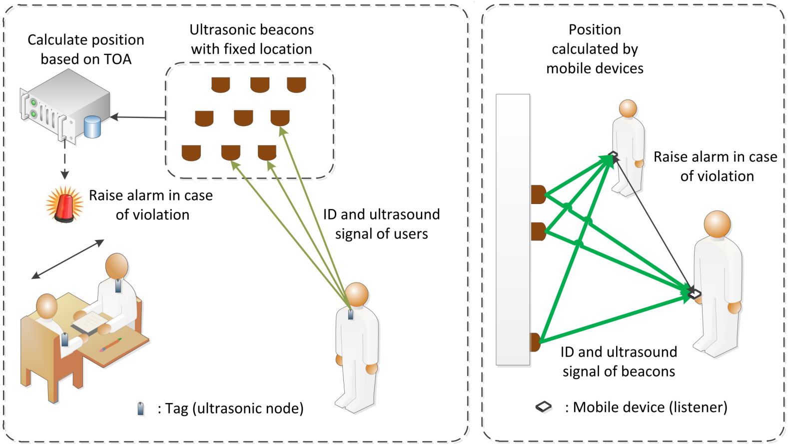
An Active Bat system (AB) [3], which is one of the first popular UPS, can be applied to keep distance among people. This AB relies on the time-of-flight (TOF), i.e., a technique to measure the distance between a sensing device and an object, of the ultrasonic signal. Specifically, as illustrated in Figure 1.2(a), an AB system contains an ultrasound transmitter, i.e., ultrasound tag, embedded on the target people whose positions are required to be located. This transmitter of each target can broadcast ultrasound signals within its coverage in an indoor environment. To receive the ultrasound signals from the target people, the system deploys an ultrasonic receiver matrix on the ceiling or the walls, aiming at forwarding the sensing information to a centralized computation system using wired or wireless connections. This centralized computer will calculate the positions of target people based on the ultrasound time-of-arrival (TOA), i.e., the constant time when the transmitted ultrasound signal is received by the ultrasound receiver. Based on the generated positions of the target people, the system can raise alarm when two people are too close from each other according to a pre-defined minimum distance between two people in an indoor environment. Due to the existence of multiple sensors at the ultrasound receiver matrix, the AB system can achieve a high positioning accuracy, i.e., 14cm. Nonetheless, this system still suffers from several drawbacks. First, the system may face a high complexity problem, especially when the ultrasound transmitters at the target people are required to transmit signals to a large number of ultrasound receiver sensors. Second, the exact locations of the target people may be disclosed as their positions are computed at the centralized conputer, thereby leading to a high privacy concern.

Cricket-based UPS

To address the limitations of using AB system, the Cricket (CK) system is developed in [4]. Instead of using the centralized computer to calculate the positions of the target people, this calculation is performed by the target people themselves who act as the receivers (as illustrated in Figure 1.2)(b)). In particular, the UBs as the ultrasound transmitters can be first deployed on the ceiling or walls. Then, the ultrasound signals along with RF signals can be transmitted to the target people. To this end, the ultrasound receiver embedded at each target people will passively receive the transmitted signals. Using the received ultrasound signals, the ultrasound receiver can compute each target people's position by itself according to the IDs and coordinates of UBs. As the ultrasound receiver only receives the signals without transmitting any ultrasound signals, the target people's privacy can be securely preserved and the complexity of the system can be reduced. In this case, the target people can send their privacy-protected positions with each other to determine whether they are too close or not and activate the alarm when they violate the pre-defined minimum distance among them.

1.1.2 Real-time Crowd Monitoring

In addition to the UPS system using TOF, UPS system can be developed based on the signal strength of ultrasound signals [6]. Thanks to the limited propagation and *confinement* feature (i.e., signal is restricted within the same room as the UBs), of



(a) (b)

Figure 1.2 Ultrasound application to keep distance among people using (a) Active Bat method and (b) Cricket method [5].

the ultrasound signals, we can use UPS as an efficient solution to detect the crowd using a real-time monitoring in public buildings, i.e., whether the target people are within the same building or not. This confinement feature is also adopted by infrared-based positioning system. However, infrared signal is not robust to the interference from heat sources including sunlight and other thermal sources, and it faces line-of-sight loss issue [6]. Therefore, ultrasound is still the most efficient technology for crowd monitoring using a signal strength-based binary decision method (i.e., whether the target people is in the same room as the UBs or not). For example, assume there exist some adjacent small rooms/buildings with a certain number of target people. One target people X has a full ultrasound signal strength coverage within its room/building. However, another target people Y has part of ultrasound signal strength coverage outside the room/building. In this case, using the binary decision approach, the system can decide whether both X and Y are in the same room/building or not without knowing the exact locations of the target people. If a certain number of people are currently in the same room/building, the system can activate the alarm to warn them that they are in a close contact, and thus some of them can move out from the room/building. Using this method, the implementation costs can be remarkably reduced as the system only require few UBs to decide the binary positions of the target people.

1.1.3 Automation

For the automation scenario, ultrasound can be utilized together with mobile robot(s) or UAV(s) in indoor environments.

Mobile robot-based UPS
A mobile robot, e.g., medical robot, may have a significant role to help minimizing physical contact levels between healthcare workers, e.g., doctors and nurses, and patients/visitors within a hospital. Using such an approach, they can keep the level of social distancing to contain some contagious viruses. For that, the use of ultrasound can take part to enhance the navigation system of the robots. For example, a robot navigation system leveraging the combination of Wi-Fi signal strength and ultrasound for indoor environments is introduced in [7]. This robot can deal with the uncertainties due to the noisy wireless channel and RF signal's multiple path effects (which is very general in crowded indoor places such as hospitals) through using an autonomous algorithm, i.e., partially observable Markov decision process (POMDP). In this case, the POMDP learning model can be used to generate environment map with more accurate localization, planning, and learning process for the mobile robot by observing the Wi-Fi signal strength and ultrasound. The observation of Wi-Fi signal strength is performed to obtain the global localization estimation, while the monitoring of ultrasound is conducted to preserve a good local environment estimation. The experimental results show that by combining Wi-Fi and ultrasound, the mobile robot can achieve high estimation rate by more than 95% of true locations and much faster convergence compared with those of using independent Wi-Fi or ultrasound observation only. This performance can be further improved when there are many people walking in the indoor environment.

UAV-based UPS
In addition to mobile robots, UAVs can also be applied to minimize physical contact of people in indoor environments. For example, autonomous UAVs can be used for goods delivery within a big building or inventory management inside the warehouse without the presence of many workers in the same building/warehouse. Nonetheless, existing works mostly study on UAV navigation for outdoor environments using global navigation satellite (GNSS), which is only efficient and accurate to be used for UAV positioning in outdoor settings. For indoor settings, the accuracy of GNSS will reduce gradually, thereby applying such the technique inside the building cannot be used directly since it may degrade the performace of UAV navigation. To address the aforementioned problem, an ultra-wideband (UWB)-based indoor localization system using autonomous UAV systems is proposed in [8]. Particularly, in addition to GNSS, the UAV systems contains ultrasound, accelerometer, magnetometer, cameras, and pressure sensor. Here, the ultrasound takes control on UAVs' height when the UAVs are in a close proximity to the ground. Experimental results reveal that by following pre-defined trajectory 10 times, the UAV systems can achieve an accurate localization with alignment error less than 10cm in an indoor setting, and thus can provide efficient autonomous goods delivery and management to support social distancing.

Important points:
Ultrasound can be utilized for social distancing scenarios including keeping distance among people, crowd monitoring, and automation. For distance among people, UPS including AB and CK systems with ultrasound transmitters and receivers are avail-

able to be used immediately to localize and inform people to safely control distance with each other. For crowd monitoring, the existence of ultrasound's confinement feature can provide efficient signal strength-based binary positioning method to detect and notify the crowd or the number of people within a building. Finally, for automation, ultrasound can help orchestrating the navigation of mobile robots and UAVs for indoor environment purposes.

1.2 Inertial Sensor

Inertial sensor, referred to as inertial navigation system (INS), is one type of sensors which can calculate position, orientation, and movement speed of a mobile object with the absence of external sources. Particularly, the INS includes two subtype of sensors, i.e., three-axis accelerometers (which can measure how fast the mobile object moves linearly with respect to mobile object direction in x, y, and z coordinates) and three-axis gyroscopes (which can calculate the angular velocity in regards to maintaining the orientation of the mobile object in *yaw*, *pitch*, and *roll*). Leveraging both accelerometers and gyroscopes, the rotation and acceleration information can be obtained to determine the orientation and position deviation of the mobile object [9]. Furthermore, the INS utilizes a *dead reckoning* approach (i.e., current position, orientation, and movement speed of a mobile object can be calculated based on the previous positions, orientations, and heading directions for particular periods) such that the INS does not require to obtain information from external references. Using such an approach, the INS can produce an accurate positioning within a short time period. Nevertheless, the above approach suffers from accumulation error over time (referred to as *integration drift*) when the current position is always measured according to the previous positions. Consequently, to maintain high-accurate positioning, the INS is usually combined with other positioning systems, e.g., global positioning system (GPS), to re-initialize the base position periodically based on the current observation of GPS [9]. As illustrated in Figure 1.3, the INS first captures position, velocity, and orientation parameters. Then, the GPS compares its captured position parameters with the captured parameters from the INS. Here, the comparison difference is applied as the input of Kalman filter to estimate the positioning error. This estimation error is finally used to adjust the output positioning parameters from the INS.

In the following, we provide several social distancing scenarios that can be performed using INS devices. Particularly, the INS can be applied to keep distance and provide automation. For keeping distance, INS-based positioning applications inside smartphones can be deployed to notify people when they are in a close proximity to each other. Additionally, the INS can be embedded into mobile robots and UAVs to control delivery and navigation applications, aiming at minimizing the physical close-contact among people.

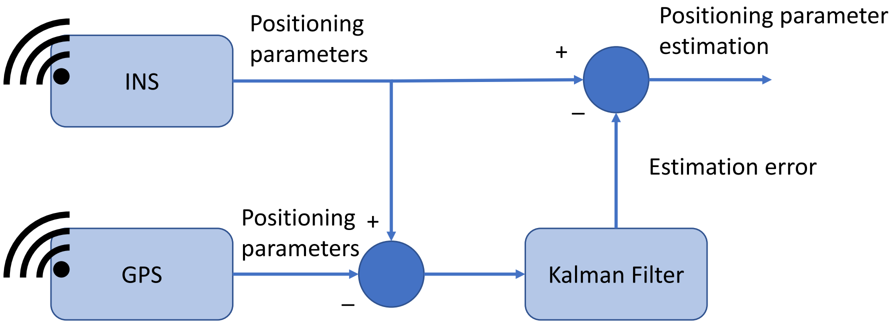


Figure 1.3 A general integrated INS and GPS system for positioning application.

1.2.1 Distance Among People

The INS has been widely popular to be applied for navigation of marine, aviation, and ground vehicle applications. Due to the proliferation of smart devices (e.g., smartphones and smartwatches) which include the embedded INS, the use of INS can be recently extended to pedestrian navigation and positioning for social distancing application such as keeping distance among people in indoor/outdoor environments (using alarm to warn people when their positions are too close from each other) as iilustrated in Figure 1.4(a). Leveraging the INS, we can obtain pedestrian positioning with a high-accuracy, especially when the INS is combined with other positioning systems for outdoor environments, e.g., GPS, Wi-Fi, and UWB.

Smartphone-based INS

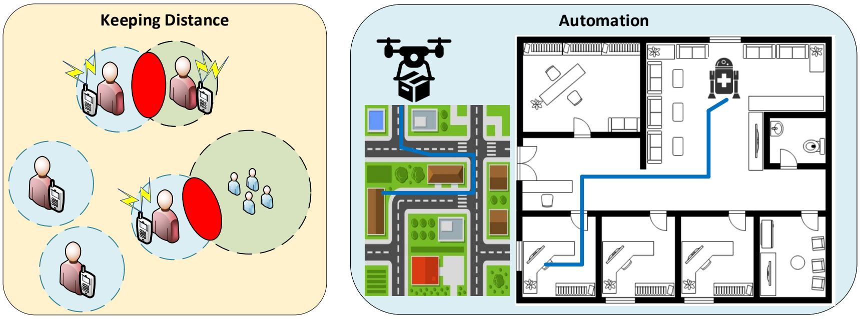
A smartphone-based indoor positioning framework is proposed in [10]. This is to deal with the fact that attaching an inertial measurement unit (IMU) on human body is not cost-effective and inapplicable. Using the existing sensors in the smartphone including accelerometer, gyroscope, and magnetometer (i.e., a sensor that can measure magnetic fields direction and strength), the framework can estimate the smartphone's current position which reflects smartphone user movement in the indoor setting. Specifically, when a mobile user starts to make a move, the captured data from those three sensors can be used to estimate current position of the mobile user along with an estimation error. In this framework, those three sensors can be utilized to detect mobile user's step, estimate mobile user's step length, and heading direction. Once the mobile user's step is detected, magnetometer and gyroscope can be used to estimate heading direction between two consecutive steps. The combination of magnetometer and gyroscope can help improving the accuracy of heading orientation calculation. This can be executed by considering an improved heading estimation algorithm to obtain the weights of magnetometer and gyroscope in the correlation function between them. The experimental results show that the proposed algorithm can enhance the positioning accuracy by 2.42 times compared with those of other conventional positioning methods.

Wi-Fi-aided INS

Extending from the work in [10], an indoor positioning system leveraging the complementary use of INS and Wi-Fi is investigated in [11]. In this case, the INS is applied to compensate the Wi-Fi's out of coverage area by providing real-time navigation with a high-accuracy using the dead-reckoning-based positioning estimation. Meanwhile, Wi-Fi positioning is utilized to deal with the common integration drift problem of the INS. To further optimally improve the positioning accuracy, a Kalman filter is used to filter duplicated INS information coming from the INS noise. Using such a system, the proposed scheme can reduce the mean positioning error by 1.53 meters. Likewise, an indoor positioning using the INS and Wi-Fi fingerprint technologies is proposed in [12]. Particularly, Wi-Fi signals and magnetic fields in the positioning target map are first measured to generate fingerprint map. To reduce the computational complexity, the Wi-Fi fingerprints are modeled using Gaussian Mixture Models (GMMs) distribution. This Wi-Fi fingerprints can be then used to improve the accuracy of the pedestrian dead reckoning method performed by the INS. Specifically, due to the integration drift problem, the dead reckoning approach is required to update the position through monitoring a reference source. In this case, the generated fingerprint map can be utilized as the reference source to update the pedestrian's position. Based on the experiments, the proposed method can improve the indoor positioning with a mean error up to 8 meters.

UWB-aided INS

In addition to Wi-Fi, the INS application can be applied together with UWB technology. For example, an indoor positioning system using the INS and UWB for pedestrian localization and tracking is discussed in [13]. Specifically, UWB, which is robust to multipath signal propagation, is used to estimate position by computing the distance between two transceivers using round-trip time (RTT) measurement of UWB signals. This UWB can also compensate the integration drift problem of the INS. Meanwhile, the INS can work to reduce high complexity and operational cost of UWB. Here, the INS can deal with the low dynamic range and external radio noise sensitiveness of the UWB. To implement the proposed framework, an information fusion method utilizing an extended Kalman filter is proposed, aiming at combining the captured data from both UWB and INS. Experimental results reveal that the UWB and INS combination can achieve better positioning accuracy with deviation 5cm in the indoor environment compared with those of other individual technology-based positioning systems. The above work is then extended in [14], where the information fusion method issue between UWB and INS is optimized to deal with the uncertainties in the measurements. Specifically, the measurements from the INS with accelerometers and gyroscopes are combined with TOA measurements from UWB to estimate 6-D pose of INS using multiple IMUs and UWB devices attached to a human body. Instead of using the extended Kalman filter, an optimization problem using a *maximum-a-posteriori* estimation and UWB calibration using a *maximum-likelihood* formulation are executed. From the experiments, the positioning accuracy can be significantly improved with root mean square error 3cm.



(a) (b)

Figure 1.4 Inertial sensors-based applications for mobile user positioning to (a) keep distance and (b) automation using UAVs and medical robots [5].

1.2.2 Automation

The use of INS can be extended for social distancing scenarios where autonomous devices are involved in, e.g., delivery services using UAVs and navigation using medical robots, as shown in Figure 1.4(b).

Mobile robot-based INS

For healthcare services, the INS has been widely used within the medical robots to assist surgeons and the movement of patients as well as deliver goods for patients with minimum physical contact between healthcare workers and patients. For example, an INS application leveraging a dead reckoning localization approach for a mobile robot is developed in [15]. Specifically, an odometry (i.e., a motion sensor to detect robot movement), which is embedded on the mobile robot's wheels, is used to predict the mobile robot's position. Nonetheless, the limitations of using odometry, i.e., big error due to wheels' slippage, system mismatches, inaccuracies of the measurements, and noise, trigger the use of INS with the dead reckoning approach without considering external sources in indoor settings. To enhance the accuracy of inertial measurements, an error model using Kalman filter is developed. This filter can also approximate the velocity and orientation of the mobile robot under the presence of noises from using the INS. The experimental results demonstrate that the proposed solution can achieve a higher accuracy compared with that of using individual odometry. In [16], a UWB-and-INS-based indoor robot positioning system using an adaptive Kalman filter is discussed. This aims to minimize the accumulation error generated by the INS. To derive error equations of the accelerometer and gyroscope, an *auto-regressive* algorithm is utilized. The simulation results show that the use of the proposed Kalman filter can improve the positioning accuracy compared with that of conventional Kalman filter (with an accuracy level less than 0.24 meters, which is sufficient for practical settings).

UAV-based INS

For delivery services, UAVs can be used to deliver goods or other stuffs from one location to another location with minimum physical contact between the sender(s) and receiver(s). Different from mobile robots using the INS that are widely used for indoor settings, UAV-based INS is mostly utilized for outdoor settings. Additionally, the navigation of a UAV is also more complex than that of a mobile robot due to the altitude consideration in UAV system. For example, the authors in [17] present a quad-rotor UAV-based navigation system using the INS and camera sensor which can perform multiple autonomous activities, e.g., take-off, positioning, and landing, in an outdoor environment. Specifically, the combination of INS and camera can help to obtain the position, velocity, and altitude of an UAV. In this case, the camera embedded on the UAV can first record images from a nearby outdoor environment and then send them to the centralized server. This server can process the images to generate the position of UAV with respect to the captured environment. The generated UAV's position can then be integrated with generated UAV's position from the INS through a Kalman filter, aiming at determining final estimated position and velocity of the UAV. Through real-time experiments, the proposed framework can estimate 3-dimensional position and velocity of the UAV accurately with frequency rate 13Hz. In [18], the authors develop UAV navigation and positioning system using a resilient fusion method between the INS and camera sensors. Particularly, two observers that utilize the INS and camera sensors perform two different activities. The first observer measures the UAV orientation according to the readings from the gyroscope and camera sensors. Meanwhile, the second observer calculates the UAV position and velocity based on the reading from the accelerometer and camera sensors. To reduce signal errors and estimate gyroscope as well as accelerometer biases efficiently, a nonlinear complimentary filter is used for each observer. The experimental results reveal that the measurement from the camera sensor can be applied to minimize the errors from using low-cost INS and shorten moving time, and thus a high positioning accuracy can be achieved for the UAV.

Important points:

Inertial sensors (i.e., the INS) that are embedded in mobile and autonomous devices, bring opportunities for the development of social distancing scenarios including keeping distance among people and automation. For distance among people, mobile devices, e.g., smartphones and smartwatches, can be used to determine the position of mobile users especially in indoor settings. In this case, the gyroscope of INS can measure the orientation of the mobile users while the accelerometer of INS can calculate the position and velocity of the mobile users. The fusion method using INS-GPS, INS-Wi-Fi, and INS-UWB can further improve the positioning accuracy and hide the limitations of using an individual INS. For automation scenario, the INS can be applied in indoor/outdoor settings using mobile robots and UAVs. The use of INS in this scenario, especially when it is integrated with camera sensors, can help to enhance the positioning and navigation efficiency through providing more accurate paths and short moving time.

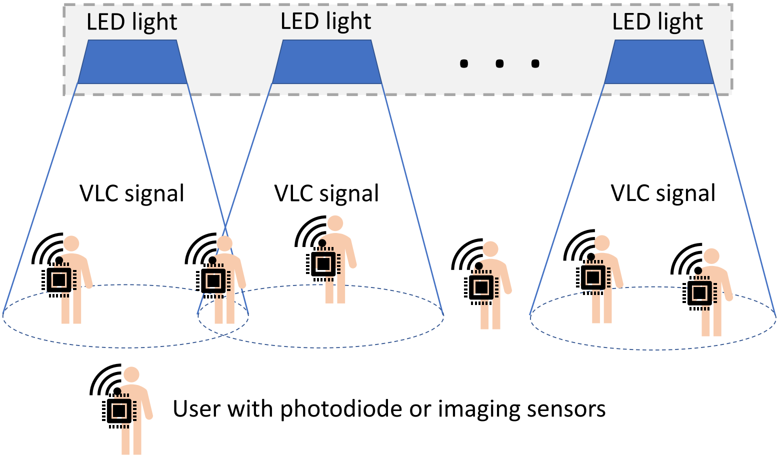


Figure 1.5 A general VLC system for positioning application.

1.3 Visible Light

The emerging evolution of visible light using light-emitting diodes (LEDs) illumination for communication (referred to as visible light communication or VLC [20]) and positioning (referred to as visible light positioning or VLP [21]) applications has triggered various use of this technology to deal with social distancing scenarios. The key benefits of using visible light are its capability to provide high flexibility, accuracy, reliability, resiliency, energy efficiency, and security [20, 22, 23]. Additionally, the ability of LEDs to provide unnoticably fast switching into different degrees of light intensity can be utilized as the potential efficient data communication method. For example, two different degrees of light intensity in a typical on-off-based modulation scheme can be represented as data bit ‘0’ (low light intensity) and ‘1’ (high light intensity). Visible light signals also do not drive any interference to RF signals. Hence, they can be deployed in various indoor settings efficiently such as schools, hospitals, schools, workplaces.

Generally, VLC systems incorporate two main components as illustrated in Figure 1.5. The first component, i.e., LEDs, works as the visible light transmitter to transmit important signals from users, e.g., positioning information. The second component, i.e., photodiodes or imaging sensors (e.g., cameras), operates as the visible light receiver to receive the transmitted signals [20]. In this case, white visible light has been widely utilized for common ilummination for both indoor and outdoor environments due to similarity of an object’s color when it is seen under white light and natural light. For communication purpose, VLC can be categorized into two modes including infrastructure-to-device communication and device-to-device (D2D) communication. For infrastructure-to-device communication mode, VLC via LEDs can illuminate an entire indoor setting, e.g., a room, such that the visible light can send user data to various devices within the room. Meanwhile, the LEDs attached at the street lamps or traffic lights can be applied to provide internet access to pedestrians or vehicular users. For D2D communication, pixels of LED display from a smartphone user can be utilized to exchange data to the camera of another smartphone user. It is worth noting that VLC is only commonly used for downlink transmission. Here, the uplink transmission from users' devices can be performed by using RF signals, Bluetooth [24, 25], or infrared [26] to minimize observable distraction from using LEDs [20].

In the following, we present some social distancing scenarios that can be implemented using VLC due to the massive presence of LED lights in today's human daily life. Specifically, VLC can be applied for photodiode-based or camera-based real-time monitoring leveraging advanced positioning methods. Furthermore, VLC can be used to provide automation including information navigation system and autonomous robot. VLC can also be utilized to control traffic on the roads, especially when high road traffic condition may trigger a huge-packed people density in a particular area.

1.3.1 Real-time Crowd Monitoring

The utilization of VLC based on LED lights can produce accurate positioning and navigation applications for both indoor and outdoor settings. To keep up social distancing purpose, VLC can be executed to detect crowd in particular public places as illustrated in Figure 1.6(a). For that, there exist two types of receivers that can be applied to realize those scenarios, i.e., photodiode-based and camera-based VLC.

Photodiode-based VLC

Photodiode has been considered as one of the most well-known VLC receivers due to its inherent benefits including low cost and easy deployment. Here, a photodiode or a set of photodiodes can work as a moving tag which is embedded into mobile users or mobile objects, e.g., shopping carts, mobile robots, and vehicles. When each mobile user utilizes this moving tag, he/she can execute a self-positioning mechanism leveraging triangulation method, aiming at keeping away from crowded places. Additionally, the collected positioning data from the sensing process of moving tag can be shared to the central server (which is owned by particular authorities/officials) to observe a large group of people in certain public places. Upon receiving and processing the positioning data, a particular service provider can notify or warn people in the considered public places through diversifying the color temperature of the lights in the crowded places. For example, when there exist high-density and low-density people in the considered areas, dark color and bright color can be applied, respectively. Note that the aforementioned approach will protect any sensitive information of the mobile users since the communication is only between the LED light fixtures as the VLC transmitters and photodiode-based moving tags as the VLC receivers.

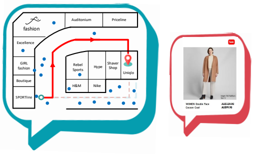
To improve positioning accuracy for people wearing photodiode-based tags in indoor settings, an advanced method that use a hybrid mechanism, i.e., angle-of-arrival (AOA) and received signal strength (RSS)-based VLC system, for 3-D localization is proposed in [27]. Specifically, the VLC receiver that uses AOA-based VLC system can obtain its location by itself through observing illumination direction of LEDs using a *least-square* estimator. To further improve the accuracy of the positioning based on AOA, RSS-based VLC system can be considered through utilizing a *weighted-least-square* estimator. From the simulation results using four visible light access points, the influence of LEDs-based VLC transmitters' orientations towards the estimator performance can be investigated with the positioning error less than 1 meter. In [28], an AOA-based positioning leveraging multi-element LEDs-based VLC transmitters is investigated. In particular, each LED in multi-element transmitters can be directed into different targets. For example, in a circular deployment of LEDs, a VLC receiver can distinguish which LED fixture that the angle of visible light comes from through the AOA-based VLC detection. Upon collecting positioning data, a Kalman filter is used to boost the positioning precision. Based on the simulations with different topologies of VLC transmitters and receivers, the proposed system can achieve the positioning accuracy less than 0.2 meters in average. Nonetheless, the main drawback of photodiode-based VLC system is the mandatory requirement to attach the photodiode devices on the mobile users/objects to receive the LED illumination signals. This may incur a failure location detection when the mobile users/objects do not carry the photodiode devices. To address this issue, pureLiFi company (https://purelifi.com) lately has developed a small optical device that can be embedded into smartphones to operate as photodiode-based VLC receiver, aiming at implementing localization services with high accuracy [29].

Camera-based VLC

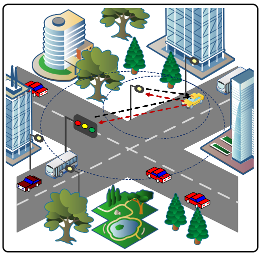
The explosion of mobile traffic demand using smart devices, e.g., smartphones, has triggered the development of VLC-based applications, e.g., navigation and indoor positioning, on mobile users' smartphones, e.g., Lumicast [24], Atrius Personal Navigator [25], and Carrefour Retail Systems [30]). Instead of using photodiodes, front-facing cameras of the smartphones can receive VLC signals which may contain visible light beacons and localization information (i.e., LED fixture's ID and location), as similarly implemented in [31]. Specifically, using an on-off keying technique, the commercial LED lights can transmit their localization information to multiple mobile users' smartphones. By capturing one single image frame using AOA-based cameras, the smartphones can observe the light presence in the image, process the received LED fixture's ID and location, and generate the location and orientation of the smartphones with respect to the directions of LED lights. The image capturing process can also be frequently executed to update the positions of the smartphones. In this case, upon capturing photos from the cameras frequently, smartphones will send the photo information to the central server for the centralized image processing. If visible light beacons exist, the important beacon information such as ID and coordinates can be extracted and transmitted back to the smartphones. To this end, the AOA-based positioning algorithm is executed to accurately approximate the location and orientation of the smartphones. Recent works using camera-based VLC positioning systems are also investigated in [32, 33, 34].

From the practical implementations of camera-based VLC system in [24, 25, 30], we can develop an interesting social distancing scenario to help mobile users

(a) Real-time monitoring and assistance systems.



(b) Information navigation systems.



(c) Traffic control systems.

Figure 1.6 VLC-based applications for (a) real-time crowd monitoring and assistance systems (indoor), (b) information navigation systems (indoor), and (c) traffic control systems (outdoor) [5].

in the shopping malls or supermarkets finding their desired products quickly in a real-time manner. Furthermore, we can use the aforementioned implementations to help mobile users discovering less crowded areas in a proactive way. Compared to the photodiode-based VLC, the camera-based VLC is more convenient to use since the mobile users can simply use its front-facing cameras in the active smartphones as the VLC receivers, and thus physical contacts among mobile users in the crowds can be detected and tracked immediately. Nevertheless, the camera-based VLC system also has a bottleneck, especially when image capturing is required to be performed frequently to obtain accurate positioning of the mobile users. Here, the smartphones of mobile users may consume high energy usage when tracking people in various locations.

1.3.2 Automation

In addition to real-time monitoring, VLC can be largely utilized to provide autonomous assistance for particular purposes (e.g., information or physical assistances for customers, elders, or disabled persons) when many people are located in crowd places such as shopping malls, supermarkets, city parks, hospitals, banks, and libraries (as illustrated in Figure 1.6(a) and (b)). For example, autonomous robots can help customers, elders, or disabled persons to find and bring specific stuffs. Additionally, autonomous information systems can assist customers to find locations of certain books, shops, or healthcare rooms. Such a system can help minimizing the physical contact between customers and assistant staffs for the social distancing purpose.

Autonomous information-based VLC

As implemented in [24, 25], VLC-based intelligent retail systems can also be applied to help customers in the shopping centres for autonomous information systems, e.g., sale information and product specification can be shown on the smartphone's screen when the smartphone is within the coverage of a particular LED illumination. In a museum or an exhibition hall, VLC can provide autonomous information for visitors to display certain augmented reality applications, e.g., running text or 3-D representation of paintings and portrayals [35]. Additionally, in [36], a low-budget surveillance and information system to automatically detect visitors within the museum and notify the visitors (notifications about current events or when they touch or take pictures some prohibited exhibition objects) is discussed. This aims to help minimizing close physical contacts among visitors as well as between visitors and exhibition objects in these places. Specifically, white LEDs are used as the VLC transmitters in the dark or osbcure environment with 1-meter distance to inform visitors about event notification or object description automatically. Meanwhile, light sensors based on photodiodes can be used as the VLC receivers to warn visitors when human contacts and photographing towards the exhibition objects are present. Here, the VLC receivers can replace the use of touch, infrared motion, and laser sensors due to its low-cost deployment and sensitivity to recognize bright light, e.g., when a visitor use smartphone's flashlight to take photos of objects in a dark setting, without damaging any exhibition objects. For communication, two modulation schemes using on-off keying with Manchester coding, i.e., exclusive-OR operation, and variable pulse position modulation can be combined. Experimental results show that the proposed framework can provide better security and faster data transfer rate for VLC system.

Autonomous robot-based VLC

Similar to autonomous information systems that can minimize close contacts among people, VLC-based autonomous robots can also be utilized to provide navigation and communication especially to help people in specific occasions, e.g., shopping-assistant, walking-assistant, and elderly-assistant robots [37, 38]. In [37], an indoor positioning robot that can recognize LED lights based on robot operating system is introduced. In particular, the positioning robot incorporates a VLP algorithm with three main processes including dynamic tracking algorithm using LED and region-of-interest, LED and its ID detection using machine learning-based feature recognition, and high-accurate cm-level positioning algorithm with two LEDs. Leveraging these processes, the robot can assist the aforementioned people automatically according to the movements of the assisted people. From the experiments, the proposed robot system can achieve indoor positioning accuracy less than 1cm and fast computing time within 0.08 seconds. Likewise, a low-cost and high-accurate indoor positioning mobile robot is presented in [38]. Here, the mobile robot leverages LED lights for VLP system and ensemble Kalman filter to improve positioning accuracy. Specifically, a light sensor is first used to capture LED lights and extract the distance between the LED lights and robots. Then, a forward ensemble Kalman filter is used to estimate some positioning coordinates. This forward filter is followed by the backward ensemble Kalman filter to deal with the estimation error produced by the forward filter. Finally, the smoother is applied to provide a higher positioning accuracy. Using experimental settings, the proposed system can improve the positioning accuracy less than 11.2cm with the acceptable computational complexity for robot applications.

1.3.3 Traffic Control

We can extend the applications of VLC to orchestrate road traffic volume on the roads. Typically, there exists a high demand road traffic on peak-hour periods which can incur a massive density of people in certain road areas, e.g., roads between residential areas to workplace areas and vice versa. In the existing literature, smart traffic control systems, e.g., a fuzzy intelligent traffic signal leveraging a fuzzy logic approach with embedded software and hardware device [39] and a reinforcement learning-based intelligent traffic light system [40], have been discussed. Motivated from the aforementioned traffic light systems, we can also implement an intelligent traffic control systems leveraging VLC systems to control traffic volume as illustrated in Figure 1.6(c). This aims to reduce the density of vehicles or pedestrians on the crowded roads. Here, the VLC system can provide communications between vehicular users or pedestrians and light systems, e.g., traffic lights and street lamps. For example, current passing vehicles and pedestrians can send their IDs and positioning information to the light systems via VLC using the LED-based headlights and smartphones' LED display as VLC transmitters, respectively. In this case, the light systems can receive the information from vehicles and pedestrians using VLC receivers, e.g., photodiodes or camera sensors. Then, upon processing and extracting meaningful information from the collected information, we can use LED-based street lamps or LED-based traffic lights to notify vehicular users and pedestrians on the roads regarding the current density of people on the considered road areas. The light systems on the roads can also orchestrate the vehicles and pedestrians by providing guides to let them avoiding the crowded road areas and prohibit them to enter the areas. In this situation, vehicles and pedestrians can receive the information from the light systems using dash cameras or smartphones' cameras as the VLC receivers, respectively.

Important points:
VLC system has a great potential to be widely used to support social distancing scenarios. In particular, the use of VLC can provide more advantageous performance, especially to achieve high-accurate indoor positioning and navigation, compared with the positioning and navigation applications using the conventional RF technologies. Using the illumination of visible light, we can develop low-cost smart retail systems, real-time crowd monitoring, and automation assistance system using mobile robots on a large-scale setting in various crowded public indoor areas (including shopping malls/supermarkets, hospitals, and airports/train station/bus station), aiming at minimizing physical contacts among people in the considered places. Additionally, we can build an intelligent traffic control system for outdoor environments, e.g., on the roads, utilizing LED-based traffic lights and street lamps, to further avoiding the crowds on peak hours in certain roads. To this end, designing an

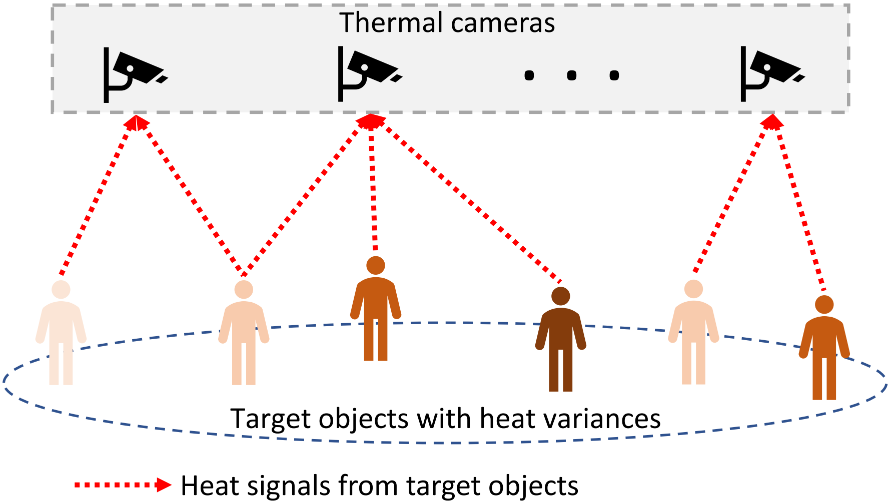


Figure 1.7 A general TPS system for positioning application.

autonomous framework which can instantly inform or warn people when they are within the crowds, e.g., by varying the colors of the lights in high-concentration areas, is of importance to provide an easy warning. Alternatively, people can move away from the crowded areas when the lights are dimmed frequently. The use of VLC can also be combined with other RF technologies, e.g., Bluetooth and infrared, to guarantee that the positioning and navigation services are not disrupted when the smartphones's camera or LED display is not being used by the mobile users. e.g., when the smartphones are in the pocket or bags. Nevertheless, VLC can only be used perfectly when there exist less ambient lights and sunlight [20, 22]. The reason is that the ambient lights and sunlight may interfere the communication of visible light, which then leads to the poor performance of RSS-based positioning systems and outdoor-based communications.

1.4 Thermal

Aside from ultrasound, inertial sensor, and visible light, thermal technology which is referred to as thermal-based positioning systems (TPS) can be utilized to support social distancing scenarios, e.g., to detect people and objects, under severe conditions including dark setting as well as fog-filled, smoke-filled, or snow-filled environments. In thermal technology, objects or people can be recognized based on heat variances, instead of light intensity as illustrated in Figure 1.7. The hotter an object is, the more thermal energy it releases. Here, the heat variances can be displayed as shades of grey or various color palettes. For example, when two target objects have different thermal energy, it can be observed clearly based on their dissimilar colors regardless the lighting conditions. Nonetheless, although TPS can monitor the objects through the aforementioned extreme environments, it is unlikely that the TPS can see a hidden object through thick walls (except that the hidden object triggers a sufficient temperature gap, the TPS can sense the object on the wall's surface).

Generally, TPS can be categorized into two major types: (1) infrared positioning (IRP) and (2) thermal imaging camera (TIC). For IRP system, it usually requires a low-cost deployment with a short-range observation, i.e., up to few meters, to detect the position of target objects via infrared energy based on AOA or TOA techniques [41, 42, 43, 45]. In this case, to localize a target object, the IRP receiver needs to be considerably close from the target object. Meanwhile, TIC uses a thermal camera to develop heat, i.e., thermal energy, images from the target objects with a longer-range, i.e., up to few kilometers [46, 47]. As such, to measure a body temperature via human's surface skin, the TIC does not need to be physically close to the target people being examined. Compared to the camera-based VLC, TIC has lower resolution (fewer pixels) sensor. This is because the thermal sensor is required to sense a larger-wavelength energy than the VLC receiver.

In the following, various social distancing scenarios considering IRP and THC are investigated. In particular, IRP can be applied to keep distance among people, physical contact tracing, and real-time monitoring. THC can be utilized to provide real-time monitoring including symptom and vulnerable group detection.

1.4.1 Distance Among People

To keep distance among people, IRP systems including Active Badge [43], Firefly [44], and Optotrak [45] systems can be applied.

IRP-based Active Badge System

In the Active Badge system [43], a batch or tag that transmits a unique infrared beacon signal periodically, i.e., every 15 seconds, is attached to each target object, i.e., an office worker or staff. In this case, the unique signal can be received by fixed infrared sensors, and thus the distance between the target object and the fixed sensors can be generated to determine the location of the target object. This Active Badge system is applicable to be used for a short-range application up to 6 meters without a capability to travel via walls. Consequently, this system can be used efficiently to check the close-distance between two persons and detect crowds in small indoor environments. Despite this system only requires low-cost and easy deployment, the use of periodic unique signals can only identify the location of target object periodically, i.e., 15-second time interval. Hence, it may reduce the accuracy of location when the target object moves frequently.

IRP-based Firefly and Optotrak System

To improve the localization accuracy especially when a target object moves quickly, Firefly [44] and Optotrak [45] systems can be executed. Particularly, for Firefly systems, an infrared camera, i.e., Firefly capturing camera, can calculate a real-time 3D position of a target object (i.e., a circle movement of an athlete) wearing an infrared transmitter, referred to as a light source marker. In this case, the infrared camera can identify the diameters and center positions of multiple circle shapes based on the light sources attached to the target object. Since a target object only wears one marker, the Firefly system can determine the 3D position of target object accurately. To further monitor the movement of target object accurately, the Optotrak system can be implemented using multiple infrared cameras as the markers. The signals transmitted from these markers are measured at various depths of the sensor receivers in multiple conditions including motion, static tilted, and static vertical. The experimental results show that the Optotrak system can provide a very good precision for people motion monitoring with the accuracy between 2 and 4 meters. Nonetheless, the Firefly and Optotrak systems are not reliable to the interference from other light sources, e.g., sunlight and light bulbs. Based on the drawback, these IRP systems are mostly suitable to be implemented in a dark or less-light conditions within small rooms.

1.4.2 Physical Contact Tracing

In addition to keep distance among people, Firefly and Optotrak systems [44, 45] indirectly can be utilized to perform the contact tracing scenario since both systems can identify people movement accurately. Specifically, multiple markers can be embedded into a body part, e.g., on waist, fingers, or ears, of target object, that is usually used to make a physical contact, e.g., hugs, handshakes, or cheek kissing. As observed in Figure 1.8, the IRP system can capture the movement of the body part and then send/store the motion information to a centralized server for contact tracing analysis, e.g., to determine the close contact between the target object and other people based on the pre-defined distance between the target object and other people through their IRP devices. This physical contact information can be saved to efficiently trace and warn other people when the target object suffers from a contagious virus.

1.4.3 Real-time Monitoring

TPS can also be utilized for real-time monitoring including road traffic monitoring, crowd monitoring, and vulnerable group monitoring.

IRP and TIC-based traffic monitoring

IRP and TIC systems can be implemented to support road traffic monitoring in less-light conditions, e.g., in the evening or at night, as illustrated in Figure 1.9(b). In [48], a robust vehicle monitoring using the IRP in diverse environments, e.g., thick fog and snow, to determine level and flow of the road traffic is proposed. Specifically, the reflected thermal energy from vehicles' tires can be used to detect the number of vehicles on the roads. In this case, the proposed system first performs a spatio-temporal image processing and vehicle pattern recognition. To improve accuracy of the vehicle detection, a misdetection correction method using a matching method is used. Then, to further determine each vehicle's position and categorize its movement speed, the combination between spatio-temporal image processing and vehicle pattern recognition can be utilized. From the experiments, the proposed system can accurately detect most of vehicles on the roads up to 92.8% with small false detection rate. Nevertheless, as IRP system can only work well for a short-range application,

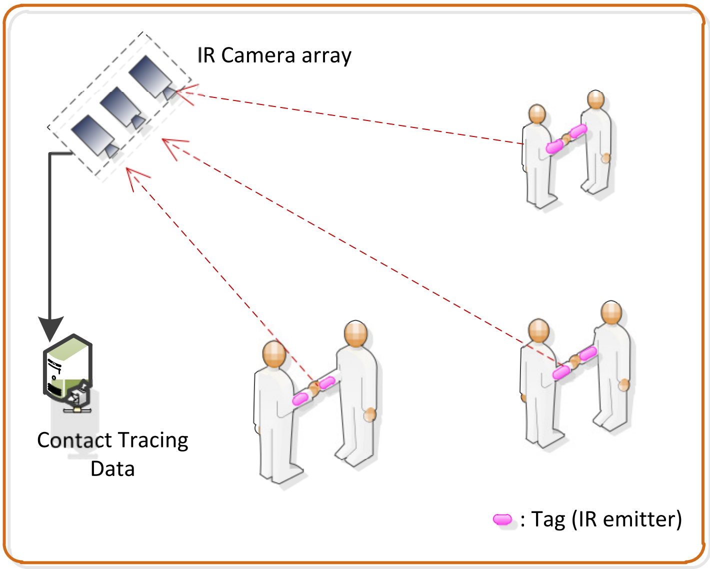


Figure 1.8 A physical contact monitoring using IRP system. If there exists a close contact between two persons, this activity can be stored for future use, e.g., contact tracing [5].

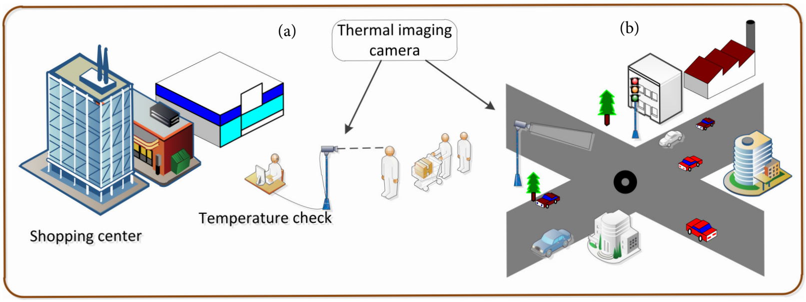


Figure 1.9 TPS applications for (a) body temperature checking of a vulnerable group using the thermal camera, i.e., TIC, and (b) real-time traffic monitoring especially in a dark or less-light situation, e.g., in the evening and at night, using IRP and TIC [5].

the use of TIC system can further improve the vehicle detection accuracy especially in a larger area with high vehicle traffic volume.

TIC-based crowd monitoring

Leveraging the TIC's advantage to detect target objects in a large monitoring area up to few kilometers, TIC can be useful to implement many real-time monitoring applications without high-accurate positioning requirement including crowd monitoring in public buildings, closure violation monitoring, and non-essential trip monitoring. For example, a joint framework which combines thermal-visible fusion sensors, i.e., infrared and visible cameras, for people tracking system using wide-range videos is discussed in [49]. These thermal-visible fusion sensors are useful to provide more accurate trajectories of a target object. Particularly, the thermal camera performs the thermal video tracking while the visible camera implements the color video tracking. The combination of both cameras then can be used to detect the target object's trajectories accurately. In [50], a UAV-aided TIC system to implement real-time target object detection, categorization, and tracking in a large area is proposed. Specifically, a TIC attached to a UAV is first utilized to capture a thermal video of the considered area. Using an analog-to-digital converter, the analog thermal video can be converted into a digital video stream. This digital video stream is then used to detect, classify, and track target objects in the considered area. Experimental results demonstrate that the proposed system can classify the types of object target accurately by 93.3% with only 5% false positives. In another work, the authors in [51] investigate human behavior-based tracking system leveraging omnidirectional TIC system. This system can provide straightforward heat-emitting object detection and uninterrupted long-term tracking. Specifically, the TIC is attached to a mobile robot to track people in various environments and light conditions based on the people's body heat levels. To speed up the people tracking estimation, a Kalman filter based on the movement behaviors of people is used. The adoption of maximum-a-posteriori-based estimation can further increase the accuracy of the people's next position according to the people's previous movement behaviors. From the experiments, the proposed system can achieve a much lower prediction error up to 60.75% and faster estimation speed by 39%.

TIC-based temperature monitoring

The TIC system can also be utilized to detect vulnerable groups, e.g., elder people and sick people, accurately, aiming at monitoring their health conditions regularly. To this end, TIC system can be incorporated to check these people's body temperature instantly from a far distance since TIC can detect emitted heat from people from few kilometers [46, 47, 52]. Moreover, the capability of TIC to determine a slightly temperature differences, i.e., with a difference gap 0.01 degree [53] can be useful to determine the sickness and health condition trends of sick people. This temperature checking using TIC can be further applied in the public places, e.g., shopping malls and supermarkets (as shown in Figure 1.9a), to remotely determine the visitors' temperature. As such, we can detect infection symptoms via the high temperature of certain visitors earlier to notify other people in the same area avoiding the infected target visitors, aiming at minimizing the spread of contagious viruses.

Important points:
Thermal-based positioning systems with short-range and long-range profiles are also useful to support social distancing scenarios especially in an environment when less-light conditions take place. Leveraging the short-range specification, IRP system is useful to provide accurate positioning to keep distance among people and contact tracing in poor-light small rooms. This is due to the fact that IRP system is easy to implement with the low-cost deployment. Meanwhile, TIC system is applicable to perform real-time monitoring for larger areas, e.g., real-time crowd monitoring and road traffic monitoring with poor-light condition, as it supports the long-range specification. Nonetheless, the high-cost of TIC system is required to be taken into account when deploying the system for commercial public areas in practice.

1.5 Summary

In this chapter, we have discussed various sensing and automation technologies to support social distancing applications. Typically, each emerging sensing and automation technology has unique features for specific social distancing scenarios. First, we have introduced the ultrasound technology, i.e., UPS, which is confined by walls and very applicable for indoor settings such as keeping distance among people, real-time crowd monitoring, and automation using mobile robots and UAVs. Second, we have presented the inertial sensor technology, i.e., INS, that can be widely integrated with smartphones or smart wearable devices to keep distance among people and automation for both indoor and outdoor environments. Third, we have investigated the visible light technology, i.e., VLC and VLP, especially using LED lights and photodiodes/camera sensors to provide autonomous assistance systems for crowded public areas and traffic control systems for outdoor settings. Finally, we have discussed the thermal-based technology, i.e., IRP (for short-range systems) and TIC (for wide-range systems), that can be utilized to support keeping distance among people, contact tracing, and real-time monitoring scenarios especially when poor-light conditions exist. All the aforementioned sensing and automation technologies can provide positioning decision with high-accuracy especially when those technologies are integrated with other emerging technologies, e.g., Wi-Fi, GPS, UWB, RF signals, and Kalman filter. Furthermore, the integration among ultrasound, inertial sensor, visible light, and thermal technologies into one intelligent system with switching mode in the future may further improve accuracy and privacy for social distancing applications in both indoor and outdoor settings as well as light and dark environments. Nevertheless, the challenges in terms of software/hardware modification and deployment/operational costs are required to be further investigated. Table 1.1 provides the summary of advanced sensing and automation technologies for social distancing scenarios based on the explanation in Sections 1.1-1.4.

Table 1.1 Summary of Advanced Sensing and Automation Technologies

Technology	Ultrasound [6, 3, 8, 7]	Inertial sensor [9, 10, 11, 12, 15, 19]	Visible light [24, 25, 27, 29, 30, 36, 37, 38]	Thermal [44, 46, 49, 50, 47]
Range	Short, restricted by walls	Not applicable	Short	few meters (IRP), few kilometers (TIC)
Cost	Low - medium	Low	Low - medium	Medium - high
Accuracy	Less than 14cm [3]	Less than 1m [9]	$\leq$ 1cm [37], $\leq$ 10cm [25, 27, 38], $\leq$ 20cm [28]	$\leq$ 0.125mm (IRP) [45], 0.9m (TIC) [51]
Setting	Indoor	Indoor and outdoor	Indoor and outdoor	Indoor and outdoor
Privacy	Low [3] - high [4]	High	High	Low - high
Existing system integration	Active Bat and Cricket systems, mobile robots, UAVs	Smartphone, mobile robots, UAVs	Smartphone, smart retail system, assistant robots	Active Badge, Firefly, and Optotrak systems, UAVs

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