CHAPTER 2

Embedded Sensors, Ubiquitous Connectivity and Tracking

Marco Arnesano and Silvia Angela Mansi

Abstract The digitalisation of the deep renovation process and built environment is enabled by ubiquitous connectivity and monitoring of the environment itself, the artefacts and actors within it, and events that occur. Such monitoring is important for efficient construction management, dynamic peak demand reduction, affordability, and occupants' well-being. Sensor networks based on Internet of Things (IoT) technologies represent an important prerequisite for both optimising and redefining the stages of the building process to meet environmental challenges. This chapter provides an overview of how computation capabilities are being integrated into the physical environment and the role of sensor networks in the context of deep renovation. The key advantages and benefits of these technologies at the pre, during and post-renovation stages are discussed together with different use cases. The value of sensor network infrastructures and the legal and ethical implications of the use of such sensor infrastructures is also discussed.

Keywords Sensing networks • IoT • Smart Buildings

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2.1 Introduction

Sensors play a pivotal role in reducing buildings' energy demand and in reaching the near Zero Energy Building (nZEB) standard through deep renovation. From this perspective, buildings should become a system that "provides every occupant with productive, cost effective and environmentally approved conditions through continuous interaction among its elements" (Buckman et al., 2014, p. 96). The Internet of Things (IoT) represents the cornerstone in the definition of a smart building (SB). Using sensor networks, SBs provide the possibility for monitoring and managing energy consumption and indoor environmental quality (IEQ) (Minoli et al., 2017).

This chapter aims to (1) define the role of sensor networks in the field of deep renovation, (2) summarise the main advantages and benefits as well as (3) the main challenges and concerns associated with the use of sensor infrastructures.

The remainder of this chapter is structured as follows. Section 2.2 introduces the key concepts for the definition of construction sites, smart buildings and services based on sensor networks. Given the importance of IoT for the deployment of innovative sensing solutions in both construction sites and smart buildings; Sect. 2.2 also includes the description of the IoT architecture together with the main communication technologies. Then, Sect. 2.3 presents various sensing use cases for the construction and renovation stages and Sect. 2.4 presents the application of sensors in smart buildings. This is followed by a discussion of ethical and legal aspects related to the use of sensor data in Sect. 2.5 before concluding.

2.2 Key Definitions, Technologies and Approaches

2.2.1 The Role of Sensors on Construction Sites

Effective monitoring of construction sites allows managers to record progress at different stages and ensure that the project stays on schedule. With the advent of sensor technology and IoT, several activities in a construction site can be monitored automatically and in real-time. The interaction between multiple stakeholders can provide a better understanding of the status of different construction activities while improving productivity and saving time and cost. Through IoT, communication and positioning technologies can also improve safety (Zhao et al., 2021) and waste management (Sartipi, 2020).

3D point cloud data represents the main approach *to mapping and monitoring* construction progress in real-life large-scale projects. This measurement system can create a digital twin of the building and identify objects present on site, capturing their external surface. Improved knowledge can be obtained with *sensor integration*, a common procedure to integrate data from different sensors to improve the quality and the accuracy of information acquired by each sensor individually. Typically, the integration involves data fusion between *mapping* sensors and *positioning and communication* sensors (Moselhi et al., 2020). While positioning sensors measure the distance travelled by a body starting from its reference position, communication sensors allow the communication between different devices. For instance, communication sensors, when integrated with positioning and mapping sensors, can be used to enhance the outdoor tracking of resources (Domdouzis et al., 2007) in a supply chain management system (Rajendranath, 2011) and the construction safety management (Park et al., 2019). The main positioning technologies are presented in Table 2.1.

Different approaches can be applied for real-time monitoring construction progress. Table 2.2 summarises the main monitoring methodologies that are currently used in real-life construction sites for understanding a particular scene, positioning objects and tracking objects.

Table 2.1 Positioning sensors in construction

Approach	*Description*
Identification and tracking devices	Radio frequency identification (RFID) is a technology for identification and data communication with devices
Inertial measurements units (IMU)	Accelerometer, gyroscope and magnetometer are used to calculate the device position
Global navigation satellite systems (GNSS)	GNSS use a satellite-based navigation system with global coverage to localise objects in outdoor spaces
Ultrasonic sensors	These sensors use ultrasound to measure time of flight (ToF) and calculate the distance
Infrared (IR) sensors	IR sensing technology detects the light reflected in the infrared region of the electromagnetic spectrum

Table 2.2 Monitoring methodologies for the construction site

Methodology	*Definition*
Scene understanding	
Classification	A process to assign a label to the scene based on a supervised machine learning (SML) algorithm (Maturana & Scherer, 2015)
Object detection	A process to localise objects of a specific category of data (He et al., 2017)
Segmentation	A method to divide data into segments representing objects (Chen et al., 2018)
Positioning methods	
Proximity	A method to detect mobile targets by using location coordinates of nearby sensors with a priorly measured position (Deak et al., 2012)
Triangulation and trilateration	Methods to estimate the target position using triangles' properties (Deak et al., 2012)
Fingerprinting	Uses a database of signals measured at known locations to estimate an object's location by comparing the current signal with the stored signals
Dead reckoning	A method to estimate the local motion of a moving target relative to a previously known position
Visual positioning	Estimates the position and orientation of sensors by using imagery and point clouds data (Zhang & Singh, 2015)
Tracking methods	
Active tracking	Tracks moving objects using different position methods (Deak et al., 2012)
Passive tracking	Involves surveying instruments such as robotic stations, stationary cameras or lidar sensors (Giancola et al., 2019)

2.2.2 *Smart Buildings and Smart Homes*

A smart building is an intelligent structure that is "*[…] expected to address both intelligence and sustainability issues by utilising computer and intelligent technologies to achieve the optimal combinations of overall comfort level and energy consumption*" (Wang et al., 2012, p. 260). An SB adapts its operation and physical form to a particular event before the event happens while maintaining its energy efficiency and occupant satisfaction (Buckman et al., 2014). SBs require many stakeholders and a lot of interconnected-embedded devices, automated systems and wireless technologies to be capable of communicating with the internal and external environment. Sensors play a pivotal role for an SB because of the need of measuring several quantities, belonging to different domains, which are required for each service deployed in an SB. Just to mention a few, electricity and heat

Table 2.3 The main services and requirements of a smart building

Service	*Details*	*Sensing requirements*
Location-based services	Identify occupants or resources' location for improving serviceability	Tracking the position of different objects within the building
Energy efficiency	Optimise the building energy consumption	Communicate with smart grids and measurement of energy loads
Facility management	Maintenance operation and control of building facilities to reduce operations and maintenance time and cost	Fine-grained sensor network for detailed real-time and long-term monitoring
Occupant comfort	Optimise ambient conditions according to occupants' needs for improving health and productivity	Multi-domain and multi-physics measurement for comfort monitoring

meters are required for energy monitoring, and environmental sensors (temperature, relative humidity, light, CO_2) are required for occupants' comfort measurement and control. Table 2.3 summarises the main functions and sensing requirements.

A *Smart Home* is the SB declination in a residential context. It is an environment equipped with technologies that make occupants' lives more convenient while preserving energy efficiency. Smart appliance solutions can cover different aspects of occupants' daily life such as air conditioning, lighting, home security, data privacy, entertainment, surveillance, detection, and assisting living (Wilson et al., 2015).

2.2.3 IoT Architecture

IoT is one of the most influencing innovations in the field of communication (Atzori et al., 2010). Its application in the built environment gives the possibility to make everyday objects intelligent and connected by means of sensing, networking, and processing capabilities (Jia et al., 2019). IoT architectures are generally described and arranged in *Perception, Network and Application* layers. The *Perception Layer* is the physical layer equipped with sensors for sensing and data collection. It detects environmental parameters and identifies other intelligent sensors in the physical space to share information to the upper layers. The *Network Layer*, as the term suggests, is responsible for processing and transmitting the raw data network technologies. The highest level is the *Application Layer*, which

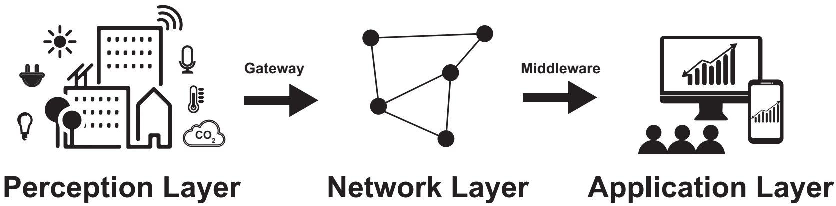

Fig. 2.1 Three-layers of an IoT architecture

creates the bridge between the building and the end user and supports the decision-making process. Figure 2.1 provides a schematic view of the three-layer IoT architecture.

Nevertheless, IoT needs to use a messaging and connectivity protocol to exchange information from remote locations. The recommended features of such protocol include (a) small code footprint (to be implemented in small devices), (b) low power consumption, (c) low bandwidth consumption, (d) low latency, and (e) use of a publish/subscribe (pub/sub) pattern. The most widespread messaging protocol is Message Queuing Telemetry Transport (MQTT), which is a lightweight pub/sub messaging transcription with a small footprint and minimal bandwidth (Spofford, 2019). Several communication protocols are available for the implementation of IoT architecture; Table 2.4 presents the most common ones.

2.3 Sensing During Construction and Renovation

Information handling is the most important aspect in industrial construction management (CM) (Wang et al., 2007). The main contexts of application in CM involve logistics, cost and time control, real-time process traceability, and operator safety (Ahmad et al., 2016). Recently, building information modelling (BIM) has been largely used in design, construction and facility management processes. The integration of sensors with BIM enables continuous monitoring of building construction stages for accurate construction and renovation management (e.g., cost and time). The integration of sensor data with BIM effectively creates a real-time digital twin that can continuously track changes and any discrepancies during the construction process. This enables the timely remediation of errors and monitoring of the condition of any material on-site by using cameras and other sensors (Liu et al., 2014). Sensor networks are also an

Table 2.4 IoT communication protocols

Concept	*Definition*
Short-range communication	
Bluetooth low energy (BLE)	A radio waves-based technology for communication between devices over short distances (2.402 GHz to 2.48 GHz)
Wi-Fi	A radio waves-based technology which allows the communication between smart devices according to IEEE 802.11 standards
UWB	A radio waves-based technology based on IEEE 802.15.4z-2020 standards, used for short-range (up to 200 metres) and high-bandwidth (500 MHz) communication
ZigBee	A high-level communication based on IEEE 802.15.4 specifications for creating personal area networks (PAN)
Long-range communication	
Frequency modulation (FM)	FM radio (88–108 MHz frequency) broadcast signals-based technology to localise the position by using fingerprinting techniques (Chen et al., 2013)
Long range (LoRa)	LoRa is an RF technology that uses a radio modulation technology for low-power, wide area network (LPWAN) communications
Sig Fox	A LPWAN communication technology, it uses Ultra-Narrow Bandwidth (UNB) modulation to send messages.
Cellular communication (CC)	CC is a way to connect people together for real-time communication and data transmission based on the global system for mobile communication standards (GSM)

efficient solution for supply chain *monitoring* and for managing building materials (Koskela & Vrijhoef, 1999). Table 2.5 the main sensor types that are currently used for mapping buildings for BIM creation and for monitoring construction sites.

BIM-sensor integration plays a key role in *preventive monitoring* during the construction phase to monitor and ensure proper structure conditions (Chen et al., 2020). IoT technologies can be used as a proactive tool to better predict building component failures, unplanned downtime, and broken tools, potentially increasing on-site productivity by up to 25% (Kayar et al., 2021). For automatic retrieval of physical information during the construction process, RFID has been widely adopted (Shen et al., 2010). BIM augmented with sensor data is also crucial for *facility management* (FM). The total cost of ownership of a building is heavily dependent on effective maintenance and the security and safety of the environment for the occupants. Several solutions have been proposed to monitor all building components to prevent failures and malfunctions

Table 2.5 Sensing construction: mapping sensors

Sensor type	*Definition*
Laser scanner (Lidar)	These sensors are based on the electromagnetic radiation near infrared spectrum for calculating the emitted pulse's time of flight (ToF) (El-Omari & Moselhi, 2011)
RGB camera	The structure from motion (SfM) approach is used for automated 3D reconstruction from digital images acquired by RGB cameras (Deak et al., 2012)
Depth camera	Cameras equipped with ToF sensors. One pulse of radiation illuminates the whole scene, thereby capturing all the reflected light. The range data are converted into an RBD-D image (Hübner et al., 2020)
Ground penetrating radar	Technologies used to map buried surface objects (Daniels, 2004)

(Cheng et al., 2020; Hemalatha et al., 2017). Finally, sensor networks can be used for monitoring the *end of life phase* at the end of the building life cycle. Tracking systems can be integrated into the building components pre-demolition to ensure traceability and the valorisation of waste (Dave et al., 2016).

2.4 Sensing During Operation: Smart Buildings

Heating, ventilation and air conditioning (HVAC) systems account for about 40% of the energy consumption of a building and therefore their optimisation is critical for SB energy management. The main monitoring functions and the related applied sensors in an SB are presented in Table 2.6.

Recent developments in affordable *IEQ* sensors enable the continuous monitoring of indoor climate and to better analyse building performance. The IEQ monitoring approach consists of deploying many independent environmental sensors to measure air temperature, humidity, carbon dioxide (CO2), particulate matter (PM), air pollutants, illuminance and noise (Choi et al., 2012). Serroni et al. (2021) developed a novel IoT system that includes an IR scanner and environmental sensors for monitoring pre- and post-renovation building performance. The monitoring of IEQ parameters, based on a non-intrusive IoT systems, allows the detection of building pathologies and such information can be used to support the renovation design. This can ultimately result in better performance

Table 2.6 Sensors applied to smart buildings

Monitoring function	*Type of sensors*
Energy	Electricity, heat meter, gas meters
IEQ	Temperature, humidity, CO_2, $PM_{2.5}$
Lighting system	IR sensor, lighting sensors
Security	IR sensor, video cameras, passive infrared (PIR)

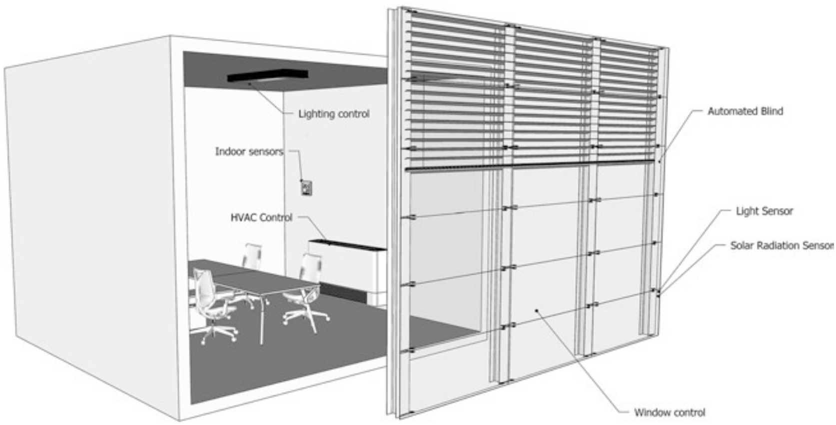

Fig. 2.2 Concept of the IoT façade module

post-renovation in terms of thermal comfort and indoor air quality. The application of IEQ monitoring to existing buildings can be facilitated with the integration of such sensors with plug and play façade modules for deep renovation. Arnesano et al. (2019), for example, propose the idea of a Smart-IoT façade. The panel is designed to embed sensors to measure indoor and outdoor conditions which are useful for the optimal control of the façade and HVAC (Fig. 2.2).

The advent of new wireless communication technologies and low-cost sensors is opening the possibility for accurate and fine-grained monitoring of the indoor environment in renovated buildings to provide HVAC and lighting systems with optimised control strategies. Kelly et al. (2013) integrated IoT and IEQ sensors in residential buildings implementing the communication between devices using the ZigBee protocol. Parkinson et al. (2019) developed a system consisting of low-cost sensors and a web platform for IEQ rating and analysis. These use cases provide evidence regarding the feasibility of advanced sensing implementation in existing buildings, thereby reducing cost and time for renovation.

2.5 Challenges and Concerns

The application of sensors in the deep renovation context is widely discussed in both research and industry as a way to increase the efficiency of the construction sector. However, managing the massive amount of data generated by both buildings and occupants creates a series of challenges and concerns that researchers and practitioners need to address.

Cloud computing has been defined as the main widespread method for sensors' data management (Mell & Grance, 2011). As cloud service providers (CSPs) typically operate using a distributed model, data can be subject to different jurisdictions. Thus, the choice of law can favour the CSP or the end user (Lynn et al., 2021). The service-level agreement (SLA) is the contract that defines the CSP's assurances on availability, reliability and performance levels for cloud service. In general, CSPs tend to minimise their liability for any loss and attempt to compensate for those issues through service credits (Bachmann et al., 2015). The rules for data management are defined by the acceptable use policy (AUP), which defines the prohibited activities and behaviours of the end users. It is important that AUP is aligned from both sides, CSP and clients, to avoid some issues (Hon et al., 2012).

Typically, CSPs are the "data processors" but also the "data controllers". The EU General Data Protection Regulation (GDPR) defines the data protection and privacy policies in case of accidental destruction, loss, or unauthorised disclosure of or access to personal data, without guaranteeing the integrity and availability of all data (Lynn et al., 2021). At the termination of the contract between a CPS and a client, an adequate provision for the subsequent handling of the client data needs to be provided (Bradshaw et al., 2011). In addition to the cloud-related data protection issues, challenges related to sensor data for automation in construction still represents a significant barrier mostly due to (1) a general lack of maturity in the use of information, (2) low level of investment in sensor technology and (3) difficulties in implementing effective communication and collaboration between stakeholders (Chen et al., 2018). In addition, industry is concerned about the lack of standardised practices for cost estimation and information security.

Considering the human side of the sensors, technologies for the end user should be capable of sensing environmental and personal contexts to ensure functional reliability. In smart homes where occupants need special assistance, failures or inaccurate inferences about the occupants' behaviour can lead to life-threatening consequences (Orpwood et al., 2005). There are significant concerns relating to privacy and security. For example, privacy could be compromised if data from IEQ sensors could provide information on the occupancy of the workplace (Cascone et al., 2017) or of the smart home (Cook, 2012). With regard to security, sensor data needs to be covered by legal protection, in case of malicious or unintentional data exposure (Sicari et al., 2015). Thus, when sensing technologies are developed, adequate consideration of the consequences of the data generated and their final use must be considered.

2.6 Conclusion

This chapter sheds light on sensing networks and their application for deep renovation, as well as considering the ethical and legal implications of their use. The introduction of sensing technologies presents opportunities to optimise and manage the construction and renovation process, from production to the end of life of buildings, and ideally both reduce costs and energy efficiency in existing buildings. Nevertheless, the huge amount of available data monitored represents a significant risk to data privacy and security. Those working with sensors and sensor data need to be knowledgeable about cybersecurity risks and appropriate mitigation measures.

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