Novel Gestural Interactions in Smart Buildings by Radar-based Sensing

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Abstract The integration of radar-based sensing technology into digital devices, non-digital physical objects, and living environments, from smart desks to smart rooms, offices, and buildings, offers a standardized technical approach to implementing always-available natural interactions, particularly those based on presence, proximity, movement, and gesture input, for ubiquitous computing application scenarios. In the context of smart buildings—as interconnected ecosystems comprising users, devices, non-digital objects, and architectural elements,—this chapter draws on the established principles of Ambient Intelligence to introduce a taxonomy of possible spatial locations for radar integration into the living environment. To this end, several application scenarios and their corresponding spatial contexts are examined, including home entertainment in living rooms, professional activities in offices and meeting rooms, and interactions for indoor navigation in smart buildings. Furthermore, this chapter explores the interaction possibilities enabled by radar-based sensing at multiple levels within a smart building, ranging from integration into small objects at the human scale, such as remote controls, to surfaces and furniture at the room scale, and entire hallways and corridors at the building scale, respectively.

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1 Introduction

Smart buildings are designed to intelligently acquire and gather actionable data from ambient sensors, users' digital devices, and third-party online services to effectively respond to evolving user needs and preferences while also complying with sustainable development and green policy practices [20]. In this context, the design of smart buildings has evolved to improve energy efficiency, enhance user comfort and well-being, and implement more robust safety measures [17, 14]. Smart buildings also provide a heterogeneous physical setting where user gesture input can be effectively acquired through radio detection and ranging-based radar sensing, and leveraged to create smart environments featuring natural interaction. Nearly any physical location within a room and, more largely, a building can be equipped with gesture sensing [37, 38], including work surfaces [7], walls [1], floors [43], ceilings [30], and windows [42], to name only a few. Even everyday objects inside rooms and offices, such as furniture or appliances, can potentially integrate radars capable of detecting presence and gesture input for users in their proximity. Beyond these spaces, exterior areas can also be similarly equipped, including corridors, hallways, elevators, and meeting points [32]. In all these settings, user input can be readily detected [21] at both short and long range through close-field and far-field radars, respectively. Furthermore, radar-based sensing can function through both soft materials, such as when integrated within a sofa, and hard materials, such as under a tabletop; see Figure 1 for a practical example with a radar mounted under a table.

Radar-based sensing enables contactless interactions with digital devices and systems [3]. Unlike video cameras or infrared sensors, which are affected by lighting and occlusion, radars function reliably in many environmental conditions. For instance, they can detect through walls and other obstacles, making them well-suited for integration into the sensor and actuator networks driving smart environments [22, 25]. From this perspective, radar sensing can contribute to the vision of Ambient Intelligence (AmI) [10] by enabling flexible, adaptive environments that feature casual and seamless interactions. Moreover, radar-based gesture sensing offers multiple advantages for interactive systems [40], among which *affordability* (since many radar devices are both inexpensive and available off-the-shelf), *ubiquity* (by allowing users to interact anywhere within the smart environment), *non-intrusiveness* (radars do not require user awareness of their locations or direct engaging with the sensor), *dependability* (by giving users a sense of control over their interactions in the smart environment), and *few-shot calibration* (by eliminating the need for sophisticated setup) [40, 41, 42]. Beyond gesture detection, radar capabilities extend to proximity and motion sensing, enabling even more interaction modalities, including human presence detection for automatic environmental adjustments, such as lighting [22]. In this context, radar functions as a continuously active sensor, dynamically adapting to the environment without requirements of direct user engagement, and contributing to sensing interactions in smart environments.

Yet, radar-based sensing for gesture interaction in smart buildings presents several technical challenges. For example, detecting fine gestures, such as finger movements and microgestures, remains a complex engineering task; interference can arise from

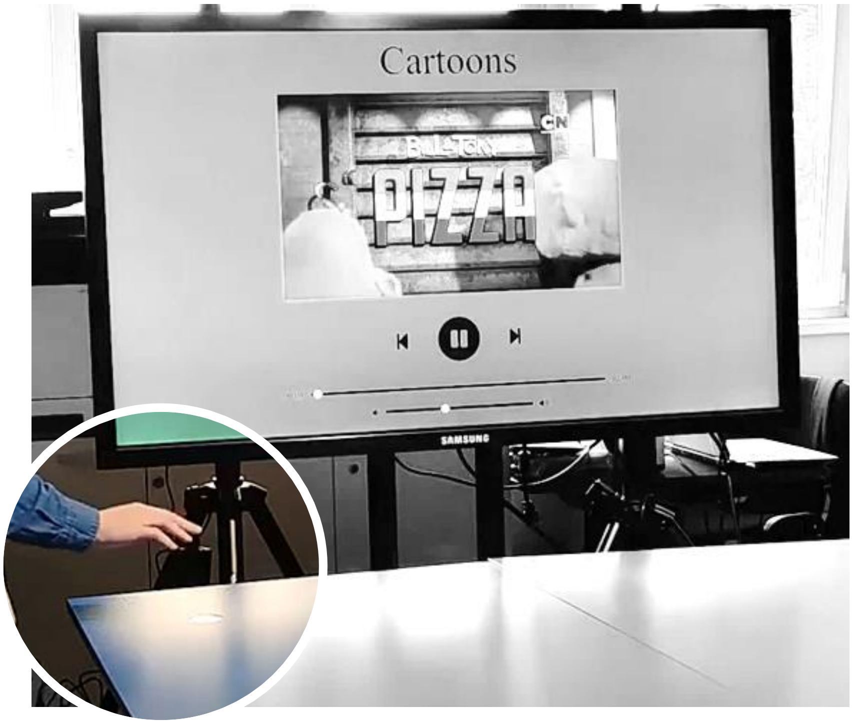


Fig. 1 An example of radar-facilitated interaction through mid-air hand gestures, where a Walabot sensor, placed under the tabletop, is used to detect directional swipes to control a video user interface on a nearby display. Source of the image: the RadarSense (2022) project.

overlapping signals, reflections from nearby objects, or the presence of other users in proximity; gestures performed at varying distances from the sensor or occlusions caused by surfaces and furniture further challenge the accuracy of radar-based gesture recognition [7, 31]; lastly, reflective surfaces, such as metallic materials and physical obstacles can distort or obstruct radar signals, leading to errors in gesture recognition that negatively impact user experience. In this context, radar placement has a significant impact on both reliable detection and accurate recognition of user gesture input. To overcome these challenges and advance radar integration in smart buildings for enabling always-available natural interactions, careful scrutiny is required for their incorporation into digital devices, everyday non-digital objects and surfaces, and living spaces.

This chapter contributes to radar-based interaction by providing a structured framework for informing the design of contactless, gesture-based input in smart buildings centered on the spatial positioning of radar sensors. It extends prior work from room-level [37, 38] to building-level integration with a proposed taxonomy that categorizes radar placement across different spaces inside a building. For example, by incorporating radar sensing into specific locations and adaptive control mechanisms, smart buildings can dynamically respond to user activity, facilitating new levels of automation beyond basic user presence and proximity detection. This approach aligns with AmI principles [10] and supports key applications, such as home automation, workspace optimization, indoor navigation, and ambient assisted living. To address a broad range of usage contexts, this chapter also explores several real-world scenarios involving gesture-based interactions in different spaces of a smart building.

2 Related Work

In this section, we provide a brief overview of recent advances in the development and use of radar technology with potential applications to smart buildings, focusing on engineering radar-based interactions and the technical challenges they present.

Radar emits electromagnetic waves and catches their reflections from surrounding objects or people, which are processed to compute distance, speed, and movement direction, enabling the detection of a wide variety of gestures, including small finger movements—a capability that positions radar as a key enabler of contactless interactions, at various body scales, in smart buildings. By facilitating gesture input of various types—mid-air hand gestures, bimanual gestures, foot gestures, and whole-body input,—radar can provide an intuitive interaction experience while reducing reliance on physical interfaces and gesture-sensing devices that need to be held or worn. Standard radar frequencies of 24 GHz and 60 GHz can effectively recognize hand, foot, and whole-body gestures, such as those defined by users. Notable implementations include Google Soli, a radar system integrated into smartphones that enables microgestures [25], and Walabot, with demonstrated utility in mid-air gesture detection in various contexts of use [39, 40]; see Figure 2 for a representative photograph of the latter and Figure 3 for examples of acquired gestures.

However, although commercial sensors provide readily-available technical solutions for integrating radar-based sensing into interactive computer systems, they may be less adaptable to custom application requirements. In contrast, customized designs of radar-based systems can address this limitation through supplemental configurations, such as specialized approaches for detecting complex gestures or integrating with other sensing technology [8, 23]. They equally present benefits when applied in specific contexts [11, 16] where off-the-shelf technology proves insufficient. Moreover, advanced technical implementations, such as mHomeGes [26], are known to achieve high gesture recognition accuracy, or leverage advanced learning architectures to optimize gesture processing, as is the case of RadarNet [12].

Machine learning (ML) and deep learning (DL) algorithms play an important role in the engineering of robust gesture interactions based on radar signal processing; see Sluÿters et al. [42] for a systematic literature review of radar-based gesture recognition. Among key ML/DL approaches, Convolutional Neural Networks (CNNs) excel at processing radar data and accurately recognizing gestures, e.g., Google Soli demonstrated sub-millimeter-level detection precision [25] and Liu et al. [26] explored the integration of CNNs with Hidden Markov Models (HMMs) in

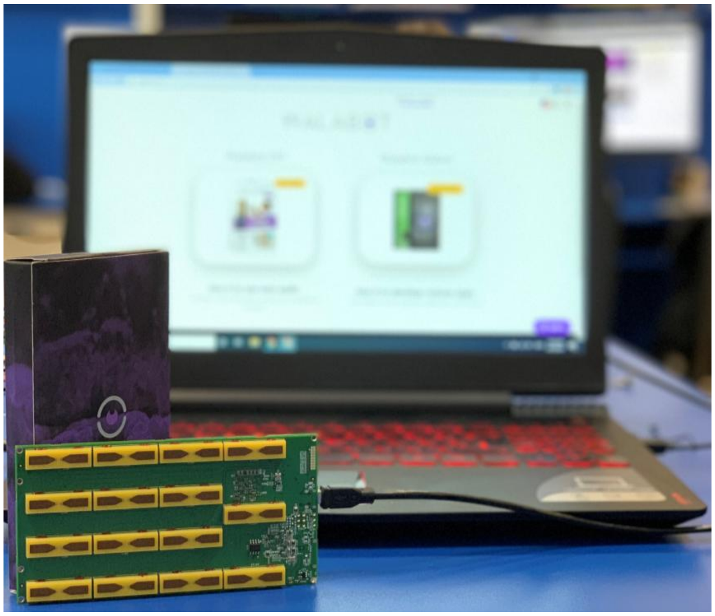
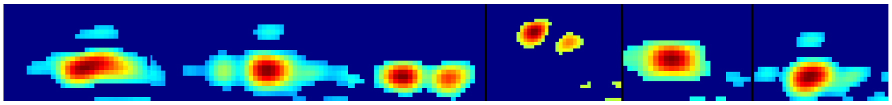


Fig. 2 Walabot device with a 15-antenna array for spatial sensing, distance, and depth measurement; see Figure 3 for examples of gestures collected using this device.

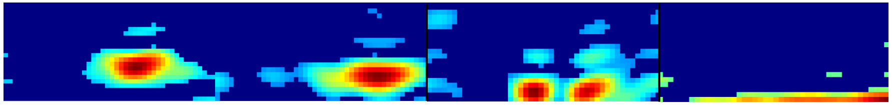


slide right
Gigie *et al.* 2019

bow
Gigie *et al.* 2019

kick
Gigie *et al.* 2019

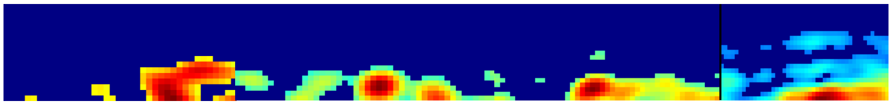
throw
Gigie *et al.* 2019



double-tap
Lien *et al.* 2016

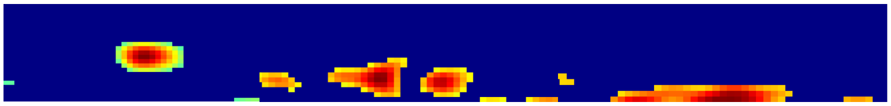
knock
Lien *et al.* 2016

touch
Lien *et al.* 2016



horizontal swipe
Lien *et al.* 2016

swipe
Lien *et al.* 2016



vertical swipe
Lien *et al.* 2016

Fig. 3 Depiction of radar-based signals, collected using the Walabot device, for various gestures examined in prior work [15, 25]; see Section 2 for details.

the mHomeGes system to integrate gesture recognition in smart home applications. Conventional ML algorithms, such as K-Nearest Neighbors (KNNs), have also been applied with robust results [33], while Long Short-Term Memory (LSTM) networks further extend the scope of radar applications in human-computer interaction, particularly in sequential input analysis. For example, Leiva et al. [22] demonstrated the integration of CNNs and LSTM models for mid-air gesture recognition through occlusive materials. Training ML/DL models requires substantial data, and data augmentation techniques have been used for mitigating dataset scarcity and enhancing radar-based gesture recognition. For example, Gigie et al. [15] improved recognition accuracy using radar data simulated from Kinect-based skeleton tracking. Their approach consisted in converting joint positions from a publicly available Kinect dataset into radar micro-Doppler signatures through a physics-based simulation framework. Other approaches, such as Sluÿters et al. [41], focused on effective radar-based gesture recognition with processing pipelines requiring minimal training.

Although gesture recognition remains an area of active research, the use of radar-based sensing extends beyond gesture commands to include proximity, presence, and activity detection. For example, Yeo et al. [49] investigated radar's potential for tracking object orientation and distance, while RadarCat [47, 48] showcased opportunities in classifying objects and materials for advanced tangible user interfaces Furthermore, radar's ability to penetrate materials enables entirely new applications, such as detecting body position and movement through surfaces [7] and walls [1, 16]. This prior work highlights the utility of radar-based sensing, supported by ML/DL algorithms, for a wide range of interaction opportunities within smart buildings.

3 Key Spaces of Radar Integration in Smart Buildings

In the previous section, we discussed how radar technology can be used in smart buildings to enable contactless, gesture-based control of interactive systems that traditionally rely on physical interaction through switches, control panels, or handheld devices [4]. For example, radars integrated into ceilings, walls, furniture, and everyday non-digital surfaces and objects can be effectively leveraged to detect user presence, proximity, movement, providing users with the opportunity of engaging in seamless interactions throughout the smart environment. To contextualize these key advantages of radar-based sensing, we now provide an overview of three representative spaces in smart buildings—*living, work,* and *transitional* spaces—where radar technology can be readily applied; see Figure 4 for an overview and Figures 5 to 8 for illustrations of these spaces highlighting their individual characteristics and opportunities for radar integration. While living and work spaces are dedicated to activities with different purposes, involving either leisure or professional tasks with distinct goals and outcomes, transitional spaces serve as links between them, facilitating movement, providing physical connections, and shaping users' perception of the architectural environment. To this end, they function as buffers [34], entry points to the building [6], and bridges between internal and external environments [19].

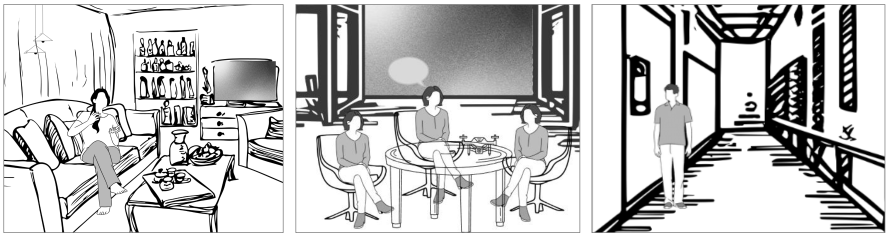


Fig. 4 An overview of radar-based integration in key spaces of a smart building, addressed in this work: living spaces (left), working spaces (middle), and transitional spaces (right).

However, similar to living and work spaces, transitional spaces offer both functional and aesthetic value, with designs that prioritize spatial efficiency and user comfort within the building [18]. In Section 4, we explore radar applications in detail with a focus on integration into smart buildings.

3.1 Living spaces

In living spaces (Figure 4, left), such as living rooms, bedrooms, kitchens, or entertainment rooms, radars can enable control of home entertainment applications, automate environmental adjustments such as lighting to align with the media being played, and facilitate interactions through contactless input, especially useful in contexts of use where the hands are engaged in another task, such as preparing a recipe in the kitchen. For example, radar sensors can enable recognition of simple hand gesture commands, such as waving to control ambient lighting or performing a circular motion in mid-air to change the TV channel [37]. Other common gestures for media control include swiping up and down to adjust volume or left and right to change the content being played. Beyond gesture recognition, radars can automatically detect the presence of users in the living space in order to adjust environmental settings and optimize energy consumption, thus aligning with green standards and sustainable building policies [20]. For example, when no one is present, the ambient system can turn off the lights and reduce the air conditioning intensity [31, 39]. Conversely, when users reenter the space, the system can restore original environmental settings and resume the media being played for optimal comfort and a seamless media experience. These outcomes, enabling sensitive, adaptive, transparent, and ubiquitous interactions, are hallmarks of AmI environments [10].

3.2 Work spaces

In work spaces (Figure 4, middle), such as meeting rooms, offices, study rooms, and workstations, radars can facilitate free-hand interactions for delivering presentations [41], enable real-time adjustments of environmental conditions to accommodate effective work and specific tasks, and be integrated into office furniture for smart desk scenarios [7, 8]. For example, radar sensors can be placed in meeting rooms to detect mid-air hand gestures, such as swipes to navigate presentation slides or circular motion to adjust video projector brightness, which would integrate the presenter's hand and body movements during their pitch. These interactions eliminate the need for remote controls and can enhance the fluidity of meetings and the intuitiveness of the presentation delivery experience [27]. Moreover, gesture commands can be detected at a distance, without requiring contact with the sensor or even direct line of sight. In complex tasks, radars could be used to distinguish among more expressive gestures that involve other body parts as well [36, 39]. Such interactions, characterized by increased flexibility, align with the AmI principles of adaptive input [10].

3.3 Transitional spaces

In transitional spaces (Figure 4, right), such as hallways, corridors, entrances, or staircases, radars can support presence, movement, and proximity detection for responsive environmental adjustments, such as involving lighting and ambient music, as well as for security monitoring, preventing unauthorized access, and detecting intrusions. One relevant use case example is navigating large buildings, such as shopping centers or hospitals, which can be challenging because of their large size and complex layout. For such application, wearable radars [22] could enhance user experience by dynamically communicating information with digital displays or lighting systems in proximity to guide users to their desired destinations. For example, when a user approaches a particular corridor, nearby digital signage could update to provide guidance on the next steps. The radar system would detect user presence in a particular location, triggering assistance from the smart building through visual signals or auditory instructions to ensure that the user stays on the correct path [24]. Another example is interactions performed through zenithal gestures [28], enabled in public spaces by ceiling-mounted cameras, typically in corridors or at building entrances, which provide a different perspective compared to conventional frontal or lateral views and, thus, enable novel interaction opportunities. Moreover, transitional spaces are public and, thus, interactive systems installed at these locations may need adaptation to users' preferred gesture commands. Such interactions, characterized by their uniform availability across building spaces, align with the AmI principles of adaptation, context awareness, and ubiquitous input [10].

4 Scenarios for Radar Integration in Smart Buildings

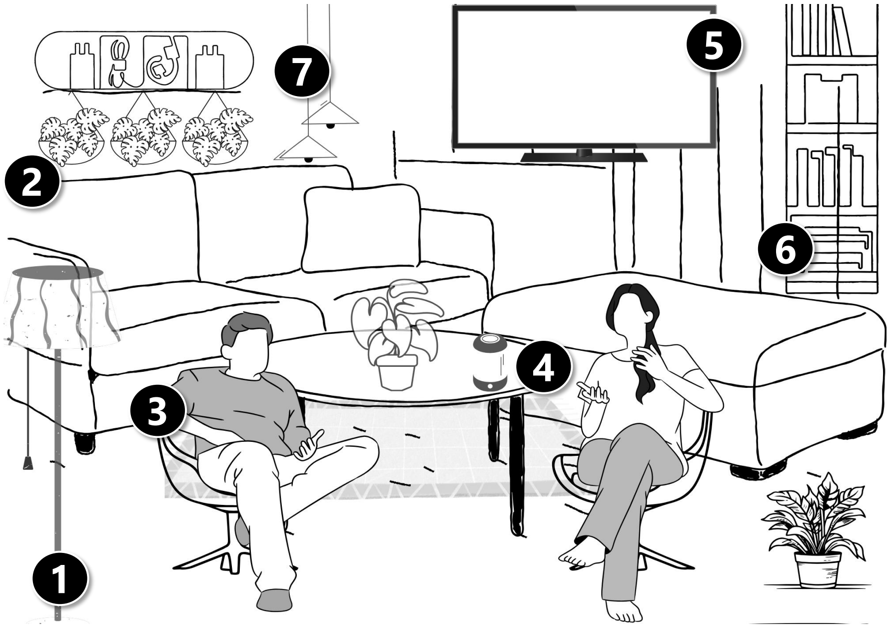
We explore the integration of radar in smart buildings by highlighting specific locations where radar sensors can be incorporated, attached, or embedded for supporting novel user interactions. To this end, we select four scenarios, presented in Sections 4.1 to 4.4, where radars are incorporated into non-digital objects, surfaces, and structural elements of the building. For each scenario, we illustrate gesture examples that emphasize elimination of the need for contact input, reduction of cognitive and physical effort for implementing the interaction, and the intuitive experience they offer to users. Our exploration builds upon prior work that has examined radar-based integration in AmI environments at room level [37, 38]. For instance, Şiean et al. [37] highlighted the potential of radar for detecting mid-air gestures in living room application scenarios through integration in TVs, digital devices, and personal robots, such as indoor drones. In a follow-up work, Şiean et al. [38] extended this contribution by examining gesture recognition techniques, application types, and engineering aspects of the integration of radar into interactive systems. In the following, we further extend their taxonomy from room-level integration to the entire building, focusing on accommodating radar-based gestures for smart building interactions.

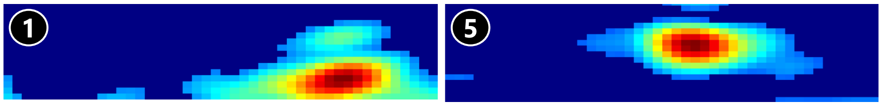
4.1 Smart furniture with integrated radar sensing

Smart furniture equipped with radar sensors could revolutionize interaction design within AmI environments. Embedding radar technology into sofas, coffee tables, or chairs, enables seamless control of home automation in proximity to everyday non-digital objects. For example, statistics show that people sit for an average of seven hours per day, making chairs an effective medium for gesture input [5]. Furniture integrated with radar can detect user gestures to control various functions in the living space, such as adjusting ambient lighting or controlling TV volume—interactions that offer an alternative to physical remote controls. Moreover, armchairs could autonomously adjust their position based on predefined user preferences, transforming conventional furniture into interactive platforms. We illustrate such scenarios with gesture examples selected from Leiva et al. [22] and Iwamoto et al.'s [16] work on radar-based gesture recognition; see Figure 5 for signals acquired with Walabot. Such advances can make furniture transcend its original purpose, becoming an active component in enhancing both user comfort and the overall experience of interacting within the smart environment.

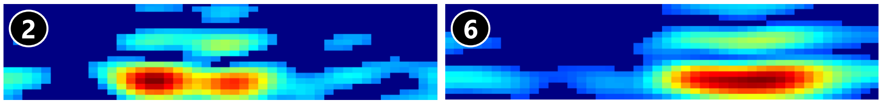
4.2 Smart entertainment with integrated radar sensing

Radar sensors facilitate freehand control in home entertainment applications, spanning from standard living rooms to sophisticated home theaters; see Figure 6. Within these spaces, mid-air gestures control volume, switch channels, or operate media playback. Prior research suggested that gesture-based input enhances immersion and usability by minimizing disruptions and improving accessibility [13, 44]. For example, studies have shown that incorporating radar-driven controls into smart home

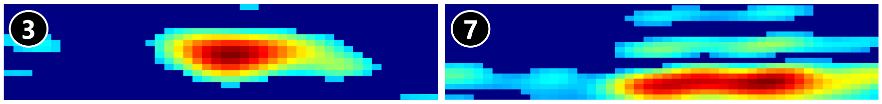




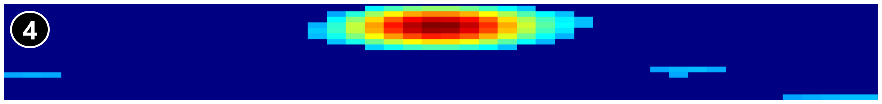
Swing right (Leiva *et al.*, 2020) Towards (Leiva *et al.*, 2020)



Swing left (Leiva *et al.*, 2020) Wiggle (Leiva *et al.*, 2020)



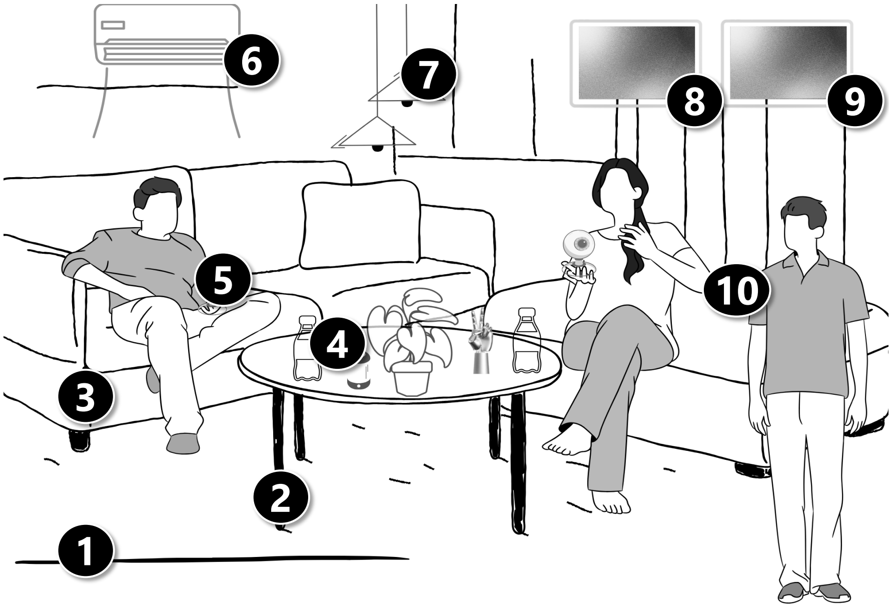
Away (Leiva *et al.*, 2020) Stand up (Iwamoto *et al.*, 2010)



Squat (Iwamoto *et al.*, 2010)

Fig. 5 Illustration of radar integration in smart furniture (top) and examples of gestures [16, 22] captured using the Walabot radar (bottom), corresponding to various integration scenarios.

ecosystems fosters greater user engagement while lowering cognitive effort when compared to traditional user interfaces [2]. Other prior work is equally relevant in this space. For example, Wang et al. [45] introduced a ML framework designed for high-frequency 60 GHz short-range radar, which combined convolutional with recur-



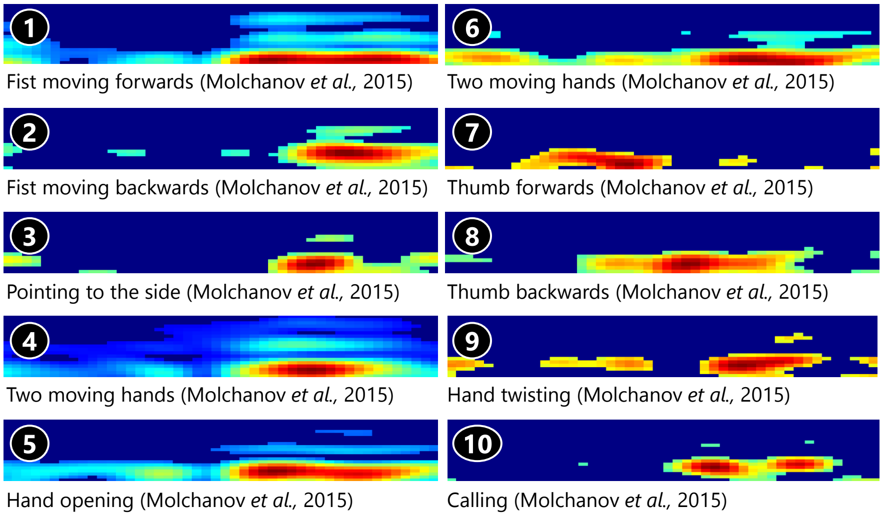


Fig. 6 Illustration of radar integration in living spaces (top) and examples of gestures [29] captured using the Walabot radar (bottom), corresponding to various integration scenarios.

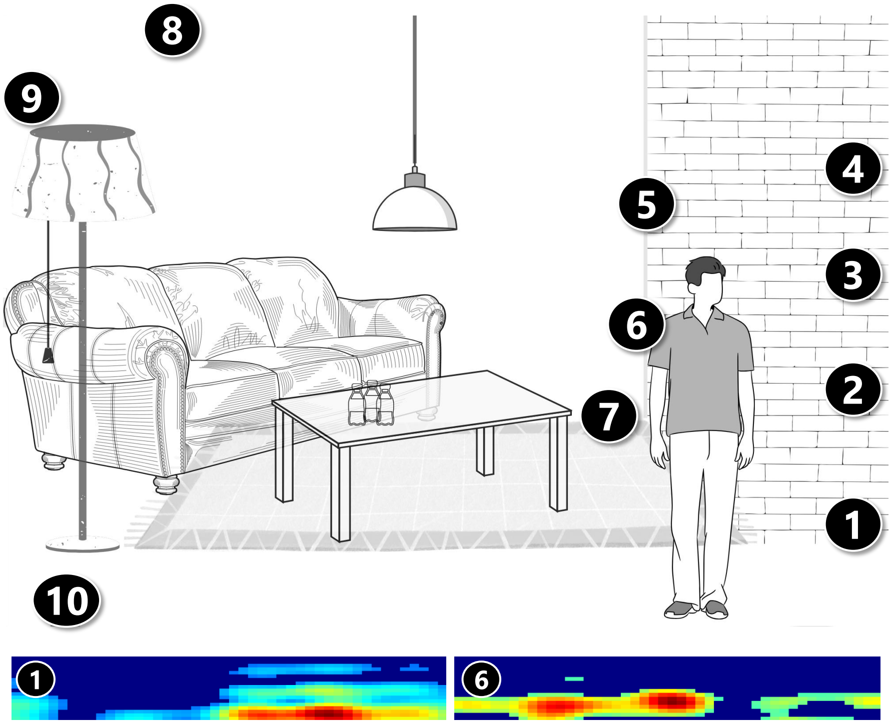
rent neural networks—the framework's capability to detect subtle finger movements enables intuitive interactions. Leiva et al. [22] explored enhanced functionality in radar-based systems, focusing on gesture recognition in situations where radar sensors are partially obscured—using a hybrid DL model integrating CNNs and LSTM components, they demonstrated mid-air gesture recognition even when blocked by materials such as leather, wool, or cotton. We illustrate such scenarios with gesture examples from Molchanov et al. [29], which addressed radar-based gesture recognition. As gesture recognition techniques continue to evolve, radar has the potential to become a standard component in smart building entertainment ecosystems.

4.3 Smart walls with integrated radar sensing

Integrating radar into walls provides a discreet method for detecting user presence, movement, and meaningful gesture commands. For instance, users could control environmental settings through hand gestures performed near walls, where a control panel would typically be located, thus eliminating the need for physical devices and interfaces. In this setup, any wall could function as a control surface; see Figure 7. This approach not only supports always-available interactions, but contributes to a cleaner, aesthetically pleasing interior design with no visible switches or control panels. Moreover, walls equipped with radar sensing elegantly exemplify AmI principles by providing seamless access to information and control. Prior work provides a strong basis for further exploration. For example, Wang et al. [46] introduced a gesture recognition system that combined Doppler radar sensing with fog computing, a paradigm that extends cloud computing by processing data closer to its originating source. We illustrate this scenario in Figure 7 with gesture examples from Patra et al. [33] and Liu et al.'s [26] work on radar-based gesture recognition.

4.4 Smart corridors with integrated radar sensing

Radar integration in hallways and corridors can enhance both navigation and user interaction capabilities. By deploying radar sensors in these spaces, user movement within the smart building can be monitored, enabling applications such as automated lighting adjustment or guided navigation; see Figure 8 for examples. These interaction possibilities build upon recent advances in radar sensing technology, as follows. Zhang et al. [50] proposed a hand gesture recognition technique based on Frequency-Modulated Continuous Wave (FMCW) radar, effectively recognizing gestures from continuous input under varying and fluctuating environmental conditions. Yeo et al. [48] examined the versatility of radar sensing for interactive systems, including user presence detection and indoor tracking. Thus, in hallways and corridors with changing architectural and lighting conditions, users could perform gesture commands without stopping or engaging with fixed interfaces. This implementation builds on the robustness of radar in diverse environments, reinforcing its suitability for complex settings. We illustrate this scenario with gesture examples from Wang et al. [46] and Pucihar et al.'s [35] work on radar-based gesture recognition; see Figure 8 for examples of radar signals of corresponding gestures. Radar integration into



Back to front (Patra *et al.*, 2018)

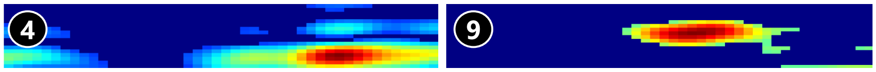
Back to front, right left (Patra *et al.*, 2018)

Front to back (Patra *et al.*, 2018)

Front to back, left right (Patra *et al.*, 2018)

Left to right (Patra *et al.*, 2018)

Front to back, right left (Patra *et al.*, 2018)



Right to left (Patra *et al.*, 2018)

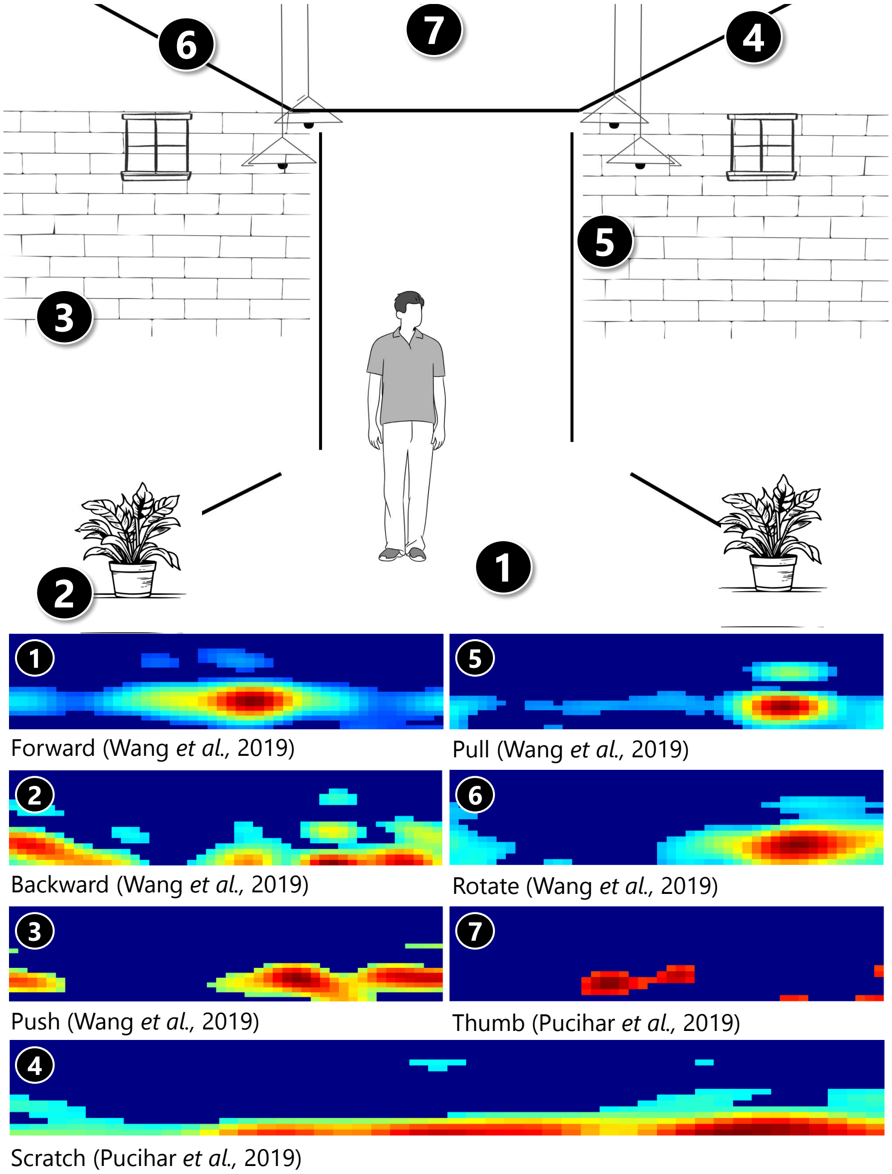
Arm up (Liu *et al.*, 2020)

Back to front, left right (Patra *et al.*, 2018)

Arm down (Liu *et al.*, 2020)

Fig. 7 Illustration of radar integration possibilities in smart walls (top) and examples of gestures [26, 33] captured using the Walabot radar (bottom), corresponding to various integration scenarios.

hallways and corridors could mark a significant step in smart building architecture, bringing everyday environments closer to reflecting AmI behavior.



Forward (Wang *et al.*, 2019)

Pull (Wang *et al.*, 2019)

Backward (Wang *et al.*, 2019)

Rotate (Wang *et al.*, 2019)

Push (Wang *et al.*, 2019)

Thumb (Pucihar *et al.*, 2019)

Scratch (Pucihar *et al.*, 2019)

Fig. 8 Illustration of radar integration in hallways and corridors (top) and examples of gestures [35, 46] captured using the Walabot radar (bottom), corresponding to various integration scenarios.

5 Conclusion

Radar technology can significantly reshape interactions in smart buildings by enabling novel input opportunities through integration in various spaces. Its distinctive capabilities, including detecting user proximity and movement even through obstacles and under varying lighting conditions, make it a key enabler of always-available, natural interactions in such environments. This chapter introduced a taxonomy for integrating radar sensors into the various spaces of a smart building, accompanied by gesture examples collected using an off-the-shelf sensor. The numerous integration possibilities reveal radar technology as a flexible solution for context-aware, user-centered smart spaces that combine functionality, aesthetics, and adaptability to their users. As radar gesture-based recognition continues to advance in terms of signal processing and machine learning capabilities, new application opportunities [3, 48] become available in smart buildings through radar technology integration.

In this context, exciting future work lies ahead in developing adaptive and intelligent environments that transcend room-level user interfaces to interactions supported uniformly across entire building spaces and even beyond [9]. Further exploration is needed, particularly in addressing technical challenges and evaluating applicability across diverse contexts of use in smart buildings, some of which were illustrated in this chapter. For instance, refining and validating the proposed taxonomy of radar integration locations is one key step in this line of work—for example, while this chapter has discussed living, work, and transitional spaces, further research could explore less conventional spaces, such as storage and utility rooms, and accommodate more architectural layouts and corresponding applications. Actual implementations of these scenarios, including conducting evaluations of gesture recognition accuracy and user performance, are equally recommended. Also, understanding the broader impact of radar-based gesture input in smart buildings remains a key research direction, where examining its effects on user experience and energy efficiency is essential for assessing long-term viability. Lastly, integrating radar sensing with other modalities, such as computer vision or audio signal analysis, can lead to the design of novel multimodal techniques adapted to smart building interactions.

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