Enhancing Accessibility in the Built Environment Using IoT-Enabled Smart Sensors

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Abstract. The built environment profoundly impacts daily life, particularly for individuals with disabilities who often face barriers to safe and independent navigation. This review explores how digital twin technologies, combined with IoT-enabled smart sensors, can enhance accessibility in smart buildings and create more inclusive spaces.
The objective is to investigate available industry solutions that use current and emerging ICT tools and assess their ability to support individuals with physical or sensory impairments. The study addresses a critical gap in the literature: the limited application of these technologies in public buildings, as most solutions are focused on home environments.
The novelty lies in the shift toward leveraging digital twins and smart technologies for real-time navigation, hazard detection, and environmental feedback, especially in public and semi-public spaces. As a methodology, a structured literature review is conducted, supported by comparative analysis and identifying research trends and gaps. Solutions are further classified thematically by disability type, context, and functionality.
The results are expected to provide actionable insights into how digital solutions can foster inclusive, user-centered environments. This review offers a short and organized synthesis of technological approaches to accessibility.

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1. Introduction

In recent years, the idea of inclusive smart buildings and cities has received growing attention, with the goal of creating environments that are accessible and supportive for all individuals,

including those with disabilities. Integrating advanced technologies into building infrastructure offers new opportunities to improve accessibility and facilitate constant mobility for people with disabilities. Despite progress in architectural design and building codes, individuals with disabilities continue to face barriers when accessing public and private spaces, restricting their participation in education, employment, and social activities.

Smart technologies hold significant potential for addressing these challenges by enabling features that enhance independent navigation and access within buildings.[1] Such solutions can improve interactions with elevators, ramps, and other facilities, offering practical support to users. By embedding accessibility considerations into design from the outset, these technologies can create environments that are inherently more inclusive.

The principle of ''Design for All'' highlights this approach, aiming to build an equitable society in which everyone can participate fully and independently. By embracing core values such as equality, accessibility, usability, flexibility, safety, aesthetics, and user involvement, these solutions have demonstrated clear benefits in improving navigation, information access, empowerment, and social inclusion. Furthermore, the integration of emerging technologies and IoT-enabled sensors offers promising avenues for enhancing the effectiveness and reach of these systems in the future.

The primary objectives of this study are to:

- Investigate available products/solutions that utilize current and emerging ICT technologies (e.g., IoT sensors, AI, real-time data processing) that support individuals with physical or sensory disabilities.
- Assess the potential of digital twin technologies to enhance accessibility in smart buildings, particularly in public and semi-public spaces.
- Classify technologies by disability type, context of use, and functionality to provide a structured understanding of the field.
- Conduct a comparative analysis of solutions, to identify research trends and gaps.

To achieve these objectives, this paper explores the current landscape of accessibility solutions, evaluates their effectiveness in meeting European accessibility standards, and identifies opportunities to improve and expand these technologies to better serve people with disabilities.

2. Theoretical Background

2.1. Design for all concepts

Design for All [2][3][4] (or Universal Design) is a holistic approach that seeks to ensure products, environments, and services are accessible and usable by all people, regardless of age, ability, or disability. Unlike designs that only comply with minimal accessibility standards, this approach integrates inclusivity as an inherent principle from the outset.

Key principles include:

- Equality and Diversity [5]: Recognizes the rights of all individuals to participate fully in society, addressing a broad spectrum of abilities, ages, cultures, and preferences.
- Accessibility and Usability [6]: Enables independent, barrier-free use for people with disabilities through features such as wheelchair access, tactile signage, and intuitive interfaces.
- Flexibility and Adaptability [7]: Supports diverse needs and preferences with customizable and modifiable solutions that evolve over time.
- Safety and Comfort [8]: Prioritizes ergonomic, stable, and sensory-friendly designs to reduce risks and enhance well-being.

- Aesthetics and Emotional Well-Being[9]: Promotes appealing designs that support positive emotional responses.
- Technological Integration [10]: Incorporates assistive technologies, smart systems, and digital interfaces to improve accessibility and personalization.
- User Involvement [11]: Emphasizes collaborative, user-centered design processes that actively engage diverse user groups to ensure their needs are addressed effectively.

In the built environment, these principles are particularly critical for people with disabilities or other vulnerabilities who may have specific requirements for indoor spaces. Features such as accessible layouts, appropriate lighting, acoustics, and environmental controls help create inclusive and supportive environments that foster participation and well-being. Ultimately, Design for All encourages architects, designers, and policymakers to prioritize inclusivity as a core value in creating a more equitable society.

2.2. EN 17210:2021. Accessibility and usability of the built environment

A key milestone in the development of harmonized accessibility requirements in Europe is the publication of EN 17210:2021, Accessibility and usability of the built environment – Functional requirements[12]. This European standard provides a comprehensive framework describing basic, common minimum functional requirements and recommendations for creating an accessible and usable built environment. It follows Design for All / Universal Design principles to ensure equitable, safe, and independent use for a wide range of users, including persons with disabilities, older people, and others with temporary or permanent functional limitations.

EN 17210:2021 emphasizes that accessibility must be considered throughout the design, construction, refurbishment, adaptation, and maintenance of buildings and outdoor urban spaces. It defines ten key accessibility domains that guide evaluation and design practice:

- Accessible and Pedestrian Areas
- Accessible and Usable Approach to a Building
- Accessible and Usable Entrances
- Accessible and Usable Routes in Horizontal Circulation
- Accessible and Usable Routes in Vertical Circulation
- Accessible and Usable Rooms
- Accessible and Usable Equipment and Facilities
- Accessible and usable toilets and sanitary facilities
- Accessible and usable exits and evacuation routes, concepts for emergency planning/fire evacuation for all
- Accessible and usable information via multiple senses

The standard was developed through broad agreement and collaboration with a diverse range of stakeholders, including ANEC (European Association for the Coordination of Consumer Representation in Standardization), EDF (European Disability Forum), AGE Platform Europe, the European Commission, ENAT (European Network for Accessible Tourism), SBS (Small Business Standards), and ETSA (European Textile Services Association). Technical collaboration also involved experts from CEN/TC 10 on lifts, escalators, and moving walks.

3. Methodology

Starting with the theoretical background of the concept of Design for All, this study adopts an inclusive approach that prioritizes equitable, safe, and user-centered design for people of all abilities. The principles of Design for All emphasize accessibility, usability, and participation from the outset, ensuring environments that serve a wide range of users effectively.

To support this approach, the research follows the framework provided by the European Standard EN 17210:2021, which defines basic functional accessibility and usability requirements. This standard identifies ten key accessibility domains that serve as a common reference for evaluating the built environment, supporting design, construction, refurbishment, and maintenance in line with Universal Design principles.

Building on this foundation, a comparative analysis was carried out to evaluate a diverse set of commercially available solutions designed to enhance building accessibility. Solutions were selected to represent the offerings of leading companies active in this sector. Data for this analysis was collected from official product documentation, technical specifications, and other authoritative sources.

The evaluation employed the ten key accessibility domains defined by the European Standard EN 17210:2021 as the analytical framework. Each solution was assessed for its functionality, accessibility-related features, and the specific disability types addressed. This systematic approach highlights both the strengths of existing technologies and gaps where accessibility needs remain unmet, providing insights for future innovation and policy development.

4. Results and Discussion

4.1. Exploring the Landscape: Products for Inclusive Living and Support in buildings

This comparative review aims to investigate the current state of the market in terms of systems and technologies developed to support people with disabilities in the built environment. The focus is on identifying solutions that are specifically designed, researched, and launched to enhance accessibility and improve the daily experience of individuals with disabilities within buildings. By analyzing the existing offerings, the review seeks to uncover market gaps and areas where accessibility remains insufficiently addressed.

The following section presents a list of 15 solutions that address various disability types and cover multiple domains of the accessibility standard for building accessibility.

1. iDS / iNS [13]– by Polara, for people with visual disabilities, are Accessible Pedestrian Signals that give safe, audible crosswalk access compliant with PROWAG standards.
2. Wireless Ped System™[14] – by Polara, for people with visual disabilities, retrofits Accessible Pedestrian Signals to give safe, audible crosswalk access without trenching or new wiring.
3. iNX [15]– by Polara, for people with visual disabilities, is an energy-efficient Audible Information Device that gives accessible, MUTCD-compliant information at unsignalized crossings.
4. Bulldog [16]– by Polara, for people with disabilities, is a durable, versatile pedestrian push button that gives reliable, accessible crosswalk activation.
5. PedApp® [17]– by Polara, for people with visual disabilities, is a smartphone app that gives remote activation and audible crossing information for APS-equipped crosswalks.
6. SEATRAC [18] – by Siemens, for people with mobility disabilities, is a remote-controlled system with a track and wheelchair-accessible seat that gives independent, safe entrance into and exit from the sea.

7. RightHear [19] – by RightHear Ltd, for people who are blind or visually disabled, is an assistive indoor navigation system that gives independent wayfinding and spatial awareness in entrances, vertical circulation, and interior routes.
8. Busch-Infoline® Call [20] – by ABB, for people with disabilities and elderly users, is an advanced modular communication system that gives reliable emergency assistance in circulation areas, rooms, and public facilities.
9. BS8300 WC Disabled Persons Alarm Systems [21] – by Johnson Controls, for people with disabilities including visual impairments, are standards-compliant emergency assistance solutions that give safe, accessible use of toilets in public and commercial buildings.
10. Honeywell EVCS-TAP [22] – by Honeywell, for people with disabilities, is a standalone emergency assistance alarm system that gives accessible, safe use of disabled toilets in public and commercial buildings.
11. Reliable Automatic Door Control & Access Systems [23] – by Disability Systems, for people with mobility disabilities, give accessible, hands-free entrance operation in commercial buildings.
12. ADAEZ Commercial Handicap Door Openers with Regenerative Drive [24] – by Disability Systems, for people with mobility disabilities, are wire-free openers that give accessible, energy-efficient entrance access.
13. Portable Wheelchair Ramps [25] – by Disability Systems, for people with mobility disabilities, give temporary, flexible entrance access at thresholds and steps.
14. Stannah Stairlifts [26]– by Stannah, for people with mobility disabilities, give safe, accessible use of stairs in homes and buildings.
15. Elevators [27] – by Marcolift, for people with mobility disabilities, give accessible vertical circulation between floors in residential and commercial buildings.

To guide this evaluation, the ten key accessibility domains defined in Section 5 of the European Standard EN 17210:2021 are used as a framework. The objective is to assess how well current technologies address the needs of people with disabilities and to provide recommendations for more inclusive, user-centered innovations.

The following table presents a comparative analysis of existing market offerings in relation to accessibility framework. The evaluation is based on the ten key accessibility domains outlined in EN 17210:2021, cross-referenced with assistive solutions currently available on the market. This approach allows for the identification of gaps where specific accessibility needs remain unmet, highlighting opportunities for further innovation and development in inclusive design and technology.

Table 1. Comparative Analysis of Market Solutions Against EN 17210:2021 Accessibility Domains

Accessibility Category	Solution Name	Description	Company	Disability Type(s)
Accessible and Pedestrian Areas	iDS / iNS	Pedestrian Signal	Polara	Visual Disability
	Wireless Ped System™	Pedestrian Signal	Polara	Visual Disability
	iNX	Audible Information Device	Polara	Visual Disability
	Bulldog	Pedestrian push button	Polara	Visual Disability, Mobility Disability
	PedApp®	Smartphone app	Polara	Visual Disability
	SEATRAC	wheelchair-accessible seat	Siemens	Mobility Disability
Accessible and Usable Approach to a Building	Portable Wheelchair Ramps	Ramps	Disability Systems	Mobility Disability
Accessible and Usable Entrances	Automatic Door Control & Access Systems	Automatic Door Control & Access Systems	Disability Systems	Mobility Disability
	ADAEZ	Automatic Door Control & Access Systems	Disability Systems	Mobility Disability
	Portable Wheelchair Ramps	Ramps	Disability Systems	Mobility Disability
Accessible and Usable Routes in Horizontal Circulation	Stannah Stairlifts	Lifts	Disability Systems	Mobility Disability
	Elevators	Elevators	Marcolift	Mobility Disability, Visual Disability, Hearing Disability
Accessible and Usable Routes in Vertical Circulation	RightHear	Audable system	RightHearLtd	Visual Disability
Accessible and Usable Rooms	-	-	-	-

Table 1. Comparative Analysis of Market Solutions Against EN 17210:2021 Accessibility Domains

Accessibility Category	Solution Name	Description	Company	Disability Type(s)
Accessible and Usable Equipment and Facilities	-	-	-	-
Accessible and Usable Toilets and Sanitary Facilities	Honeywell EVCS-TAP	Alarm System	Honeywell	Mobility Disability Visual Disability
	BS8300 WC Disabled Persons Alarm Systems	Alarm System	Johnson Controls	Mobility Disability Visual Disability
Accessible and Usable Exits and Evacuation Routes	Busch-Infoline	Communication system for emergencies	ABB	Mobility Disability
Accessible and usable information via multiple senses	RightHear	Audable system	RightHearLtd	Visual Disability

4.2 Identifying the gaps

The study examined the applicability of the above commercially available solutionsof solutions related to the 10 domains of the European Standard EN 17210:2021 for accessibility in the built environment. These domains include pedestrian areas, approaches to buildings and entrances, horizontal and vertical circulation, usable rooms, toilet and sanitary facilities, exits and evacuation routes, and the provision of information about the building through multiple sensory channels. Various accessibility solutions available on the market were identified. While these solutions demonstrate potential in enhancing accessibility, it is crucial to identify the specific gaps that this study aims to address.

While the combination of different mechanisms and products available on the market can provide accessibility solutions, there is a lack of autonomous systems specifically designed and implemented with the sole purpose of ensuring accessibility. For essence, although sensors can be used to detect movement and open entrance doors, such solutions are not explicitly designed, promoted, or tested with accessibility as their primary focus.

The solutions currently available on the market primarily address the needs of individuals with mobility disabilities. These solutions are highly beneficial for promoting the inclusion of disabled individuals, offering safer ways to access buildings, such as ramps, portable ramps, and elevated ramps to facilitate safe entry. In the domains of approaching, accessing, and entering a building, there are significantly more solutions available for people with mobility disabilities.

For individuals with visual disabilities, accessibility can be addressed through different means. One option is the use of audible applications that accurately guide users within and around the building. Another solution can be implemented during the design phase, such as using distinct exterior colors or contrasts on the building to enhance visibility and recognition for people with visual disabilities.

Furthermore, inside the building, vertical navigation for people with mobility disabilities requires clear pathways, free of obstacles or furniture that could block movement. A potential solution is the use of BIM (Building Information Modeling), which can provide users with a clear visual map of all detected objects within the building, helping them decide on the most accessible route. This type of system can also support people with visual disabilities by guiding them along safe and passable paths. In terms of horizontal circulation, elevators remain the most effective solution. Accessible-friendly features, such as Braille on buttons and audible announcements for floor detection, greatly support navigation.

For individuals with visual or hearing disabilities, having clear and readable signage is essential for orientation and wayfinding. Although many products offer partial solutions, there are still very few independent systems on the market that focus specifically on accessibility.

Furniture, toilets, and sanitary facilities play a crucial role in creating an inclusive and supportive built environment. These elements must be considered during the early stages of the building's design to ensure that accessibility and usability are integrated into the overall layout. Accessible toilets and sanitary spaces should be designed to accommodate people with diverse needs,

including individuals who use wheelchairs, have limited mobility, visual or hearing disabilities, or require assistance.

Key features of accessible sanitary facilities include appropriately positioned grab bars, non-slip flooring, emergency call buttons, and sufficient space for safe maneuverability. Toilet heights, sink designs, and mirror placements must also be adapted to suit a range of user requirements. Additionally, gender-neutral and family-friendly accessible toilets can further promote inclusivity.

There are also a wide range of alarm systems available on the market specifically designed for accessible toilets. These systems are tailored to support individuals with various disabilities as well as elderly users. In case of emergencies, users can easily activate alarms using pull cords or accessible buttons, alerting staff or caregivers for immediate assistance. These systems often include both visual and auditory alerts to ensure they are effective for people with hearing or visual impairments.

By incorporating accessible and usable equipment and facilities, including emergency systems from the design phase onward, buildings can ensure a safer, more inclusive, and dignified experience for all users. When it comes to furniture and interior equipment, selection and placement are equally important. Furniture should be arranged to maintain clear pathways and be easy to use by individuals with physical or sensory limitations.

Finally, there is a significant lack of solutions regarding exits and evacuation routes in case of emergencies. Although some products, such as clear visual signage, support individuals with visual disabilities, there are very few solutions designed for people with hearing disabilities specifically, systems that can effectively alert them during an emergency. This is a critical gap.

Moreover, when combined with the domain of providing usable information through multiple senses, it becomes clear that the market lacks comprehensive, inclusive solutions in this area. The limited availability of multisensory emergency communication tools highlights a major gap in the accessibility solutions currently offered on the market.

5. Conclusions

This research study explored the current landscape of accessibility solutions designed to improve the inclusivity of buildings for individuals with disabilities. By evaluating trends, existing accessibility applications, and their real-world impact, the study revealed both the progress made and the gaps that remain in the field of inclusive design.

The study highlighted the importance of user-centered design, the integration of established accessibility standards, and collaboration with building stakeholders as essential components for the successful development of accessibility solutions. It also emphasized the growing need for inclusive smart building features that support full and independent participation for people with disabilities in both public and semi-public spaces.

Furthermore, the research underscored the valuable contributions of EU-funded projects that aim to advance accessibility in the built environment, showcasing innovative practices and technologies. However, the study also pointed out critical gaps, particularly in the areas of

emergency evacuation solutions and multisensory information systems, which require further attention and development.

Overall, the findings of this research contribute to the evolving discourse on inclusive design and offer practical guidance for developers, policymakers, and advocates working to create more accessible environments. By addressing the identified challenges and leveraging the insights presented, stakeholders can drive forward meaningful changes and ensure a more equitable built environment for all.

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