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A Study on 3D-Based Design Guidelines for Multi-Housing Areas to Establish Robot-Friendly Living Environments

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Abstract This study proposes 3D-based robot-friendly design guidelines to introduce residential service robots (delivery and care robots) into existing multi-housing areas, which often lack adequate infrastructure and are excluded from advanced complex residential cultures. To overcome the limitations of conventional 2D drawing-based evaluation methods in reflecting the 3D maneuverability and sensor mechanisms of robots, we three-dimensionally analyzed the structural and physical limitations in multi-family and multi-dwelling houses. The analysis identified dynamic obstacles in pilotis parking lots, step differences at common and household entrances, the fundamental absence of elevators, narrow spaces, and optical noise from reflective finishing materials as key factors impeding robot navigation. To address these issues, we propose guidelines that include the installation of unmanned delivery hub-stations and robot-exclusive small lifts, step-free approach pathways, and network-linked automatic doors for public areas. For private spaces, the guidelines suggest fully flat entrances, matte and uniform flooring, the removal of thresholds, and alcove-type buffer zones with built-in docking stations to prevent pedestrian-robot interference. By applying these guidelines to a 3D prototype model of a four-story multi-dwelling house, we confirmed that modifying architectural forms and establishing minimal infrastructure can resolve physical disconnections. This research provides practical foundational data to improve technologically marginalized multi-housing culture where humans and robots coexist safely.

Keywords: Robot-friendly architecture, multi-housing, Improvement of residential environments, Remodeling, 3D-based design guidelines

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1. Introduction

1.1. Background and Objectives of the Study

The rapid progression of population aging and the increasing prevalence of single-person households have intensified labor shortages across various industries, making the introduction of service robots into residential environments an urgent necessity rather than a distant prospect. According to data released by the Statistics Korea (2024), the proportion of single-person households in South Korea has already exceeded 30%. Furthermore, the widespread adoption of contactless services and the expansion of e-commerce have significantly increased the demand for last-mile delivery robots and care robots that assist residents in their daily lives.

In response to these societal changes, both government agencies and industry stakeholders have actively established policies and standards to support human–robot coexistence within the built environment. Major initiatives include the revision of the Intelligent Robots Development and Distribution Promotion Act, the publication of the Smart Building Activation Roadmap (2023) by the Ministry of Land, Infrastructure and Transport, and the launch of the national R&D project entitled Development of Core Technologies for the Design, Construction, Operation, and Management of Robot-Friendly Buildings (2025–2028). These efforts demonstrate a growing commitment to creating architectural environments capable of accommodating robotic services.

The integration of such smart technologies into residential environments can be understood as a process of realizing a new form of complex residential culture, in which advanced infrastructure and public services are embedded within everyday living spaces. Residential architecture is evolving beyond its traditional role as a static shelter and is becoming an active platform capable of delivering diverse living services through robots as dynamic interfaces.

However, existing studies on robot-friendly architecture have primarily focused on newly developed smart office buildings and large-scale apartment complexes. Consequently,

existing multi-housing, including multi-family and multi-dwelling housing with relatively weak infrastructure, are likely to remain excluded from the benefits of this emerging residential culture. These multi-housing environments typically consist of four- to five-story buildings with pilotis parking structures on the ground floor, limited or absent elevator systems, and narrow shared stairways. Such spatial and physical constraints have rarely been designed with consideration for robotic mobility and service delivery efficiency.

Accordingly, this study aims to establish a foundation for a new form of integrated residential culture by proposing robot-friendly remodeling guidelines that optimize the operation and navigation of service robots in multi-housing, which currently remain underserved by advanced robotic services. Through the integration of smart infrastructure and public services, the proposed guidelines seek to improve the quality and accessibility of residential environments that have been technologically marginalized.

Service robots perceive and map their surroundings using three-dimensional spatial data collected through multiple sensors, including LiDAR and RGB-D cameras, during autonomous navigation. Therefore, ensuring safe and efficient robot operation requires comprehensive consideration of factors such as the robot's physical dimensions, sensor blind spots resulting from three-dimensional fields of view, overhead obstacles, and variations in floor levels.

Conventional two-dimensional drawings possess inherent limitations in evaluating these three-dimensional spatial perception characteristics and operational mechanisms of robots. To address this issue, this study proposes design guidelines based on three-dimensional geometric configurations that account for robotic spatial cognition processes and navigation constraints. Ultimately, the research aims to provide foundational data for the development of residential environments in which humans and robots can coexist safely and efficiently.

1.2. Scope and Methodology

The spatial scope of this study is limited to multi-housing composed of multi-family and multi-dwelling housing types. More specifically, the analysis focuses on the spatial perception and navigation capabilities of service robots within both shared (public) and private residential spaces.

The research methodology consists of four stages. First, a comprehensive literature review is conducted to redefine the concept of robot-friendly architecture from a socio-cultural and spatial perspective and to identify the physical specifications and operational characteristics of residential service robots. In addition, existing robot-related certification systems and standards are examined to establish the necessity of Level of Service (LOS) evaluation and three-dimensional design approaches.

Second, the spatial and morphological characteristics of existing multi-family and multi-dwelling residential buildings are analyzed to identify the key factors that limit robot navigation and the architectural obstacles encountered at building entrances, shared spaces, and private residential units.

Third, detailed design guidelines are proposed to address and overcome the identified limitations. These guidelines aim to improve the navigability, accessibility, and operational efficiency of service robots within multi-housing environments.

Finally, a prototype model is developed using a three-dimensional modeling tool based on the proposed design guidelines. Through the prototype, the applicability and effectiveness of the guidelines are examined within a simulated residential environment.

2. literature review

2.1. Concept of Robot-Friendly Architecture and Complex Residential Culture

Robot-friendly architecture refers to a built environment equipped with the infrastructure necessary to support the seamless movement and operation of robots, thereby enabling the safe coexistence of humans and robots within the same space (Lee et al., 2022). Traditionally, research on indoor robot navigation and autonomous mobility primarily focused on robotic engineering approaches aimed at enhancing sensor performance and improving Simultaneous Localization and Mapping (SLAM) algorithms embedded within robotic systems. However, as robots have become increasingly integrated into everyday life, it has become evident that improvements in mechanical performance alone are insufficient. Consequently, recent studies have expanded the scope of research toward the development of robot-inclusive environments, in which architectural spaces actively support robot perception, navigation, and interaction (Tan et al., 2016).

Residential environments are significant not merely as physical structures but as living spaces where culture is learned, shared, and continuously shaped through social relationships and residents' everyday experiences (Cheon, 2023). Within this context, robot-friendly design can serve as a key component in realizing a new form of complex residential culture that integrates advanced infrastructure with public services aimed at enhancing residents' quality of life. By enabling access to logistics, caregiving, and administrative services without requiring residents to leave their homes, robots transform residential environments from passive places of shelter into active nodes within broader social service networks (Shin, 2025).

Previous studies have explored various aspects of robot-friendly architectural environments. Lee et al. (2022) emphasized the importance of integrating architectural design, facility planning, and system connectivity through the development of certification indicators for robot-friendly buildings. Jung et al. (2023) extended this framework to the scale of apartment complexes and proposed a robot-friendly environmental certification model. Kim et al. (2023)

Table 1. Major Keywords of Previous Studies Related to Robot-Friendly Architecture

Author (Year)	Research Title	Key Keywords
Kim et al. (2019)	A Study on the Development of Robot-Friendly Apartment Floor Plans	Keywords: Robot, Apartment, Floor Plan Development, Residential Environment, Architectural Design
Lee et al. (2022)	Development of Certification Indicators for Robot-Friendly Buildings	Keywords: Robot-Friendly Buildings, Certification Indicators, Human–Robot Interaction
Jung et al. (2023)	Development of a Robot-Friendly Environmental Certification Model for Apartment Complexes	Keywords: Robot-Friendly Environmental Certification, Apartment Complex, Evaluation Indicators
Kim et al. (2023)	Establishment of Infrastructure Strategies for Implementing Robot Delivery Services in Apartment Complexes	Keywords: Robot Delivery, Autonomous Delivery Vehicle, Residential Infrastructure Development
Song et al. (2025)	A Preliminary Study on Developing LOS Evaluation Indicators for Human–Robot Coexistence in Robot-Friendly Buildings	Keywords: Robot-Friendly Buildings, Human–Robot Coexistence, Level of Service (LOS)

and Song et al. (2025) established quantitative criteria for spatial utilization by proposing infrastructure strategies for robot delivery services in residential complexes and developing Level of Service (LOS) indicators for human–robot coexistence, respectively. Furthermore, Kim and Choi (2019) demonstrated the feasibility of indoor care services through the development of apartment floor plans designed to accommodate domestic service robots.

The major keywords and research themes identified in previous studies related to robot-friendly architecture are summarized in Table 1.

However, these studies have primarily focused on large-scale apartment complexes and office facilities, with particular emphasis on the development of certification indicators, evaluation frameworks, and floor-planning strategies for robot-friendly buildings. As a result, there remains a significant research gap regarding the establishment of infrastructure that integrates public services within multi-housing. Table 2 summarizes the spatial scope and major contributions of previous studies related to robot-friendly architecture.

2.2. Types and Characteristics of Residential Service Robots

Successful robot-friendly architectural design requires a clear understanding of both the intended functions and hardware specifications of the robots to be deployed within the target environment. The primary service robots expected to be introduced into multi-housing, where single-person households and elderly residents are highly concentrated, can be broadly classified into two categories.

The first category is last-mile delivery robots. These robots exhibit integrated indoor–outdoor mobility characteristics, traveling from external road networks through pilotis parking areas and ultimately reaching building lobbies or individual residential units. Because they are required to transport relatively heavy parcels and food deliveries, they generally possess greater weight and wider wheelbases than other service robots. Consequently, they require a minimum effective passage width of approximately 800-900 mm and a turning radius of at least 1.2 m. Furthermore, they encounter substantial difficulties when navigating steep ramps or stairways exceeding gradients of 5–8 degrees (1:12–1:18). Since these robots operate under varying outdoor environmental conditions, including direct sunlight and precipitation, environmental controls capable of mitigating fluctuations in illumination levels are essential for stable navigation.

The second category consists of indoor care and domestic assistance robots. These robots are designed to operate continuously within compact residential units, typically ranging from 30 to 60 m², where they assist elderly residents with mobility and daily living activities. Although smaller than delivery robots, they must navigate through narrow spaces between furniture and architectural elements, requiring advanced short-range navigation and obstacle-avoidance algorithms. The performance of these robots can be significantly affected even by low thresholds

Table 2. Spatial Scope of Previous Studies on Robot-Friendly Architecture

Author	Spatial Scope	Description
Kim et al.	Apartment Housing	Proposed robot-friendly apartment floor plans according to housing typologies
Lee et al.	Office Facilities	Developed certification indicators for robot-friendly buildings
Jung et al.	Apartment Housing	Expanded existing robot-friendly building certification systems to apartment complexes and developed evaluation indicators
Kim et al.	Apartment Housing	Proposed spatial planning scenarios for implementing autonomous delivery services within residential complexes
Song et al.	Not Specified	Developed service-level-based design and evaluation characteristics for robot-friendly buildings supporting human–robot coexistence

of less than 30 mm, which may reduce sensor accuracy and operational stability. Moreover, because their visual sensors are highly sensitive to backlighting and strong floor reflections, they require highly uniform finishing materials and carefully controlled lighting environments to ensure reliable perception and navigation (Seo et al., 2025).

2.3. Domestic and International Certifications and Standards for Robot-Friendly Architecture

To establish integrated infrastructure environments where humans and robots can safely coexist, various certification systems and standards have been introduced both domestically and internationally. In South Korea, the Robot-Friendly Environment Certification (REEC) system has been administered by the Smart City Association since 2022, while the Ministry of Land, Infrastructure and Transport (MOLIT) has provided policy directions through the Smart Building Activation Roadmap.

According to Park et al. (2025), whereas the conventional Barrier-Free (BF) Certification primarily focuses on ensuring physical accessibility for transportation-vulnerable users, robot-friendly certification systems emphasize digital infrastructure and communication environments that support autonomous robot operations. Consequently, while BF certification evaluates physical spatial conditions such as level differences and effective passage widths, robot-friendly certification prioritizes factors including the elimination of network blind spots, system interoperability, and the implementation of machine-to-machine (M2M) communication interfaces (Lee et al., 2022).

Internationally, organizations such as Japan's Robot Friendly Asset Promotion Association (RFA) and Singapore's Building and Construction Authority (BCA) have established standards for robot-friendly environments and applied them to public facilities and commercial buildings (Yamamoto, 2019). Furthermore, these standards partially incorporate three-dimensional spatial utilization criteria to support robotic operations and facility management (Matsuoka, 2025). A summary of major certification systems and standards related to robot-friendly architecture is presented in Table 3.

However, these standards have generally been developed for large-scale buildings and newly constructed apartment complexes. As a result, they do not adequately address the cultural and spatial characteristics of aging or space-constrained multi-housing. Therefore, there is an urgent need to establish practical guidelines that enable residents of multi-housing neighborhoods to benefit from advanced robotic services regardless of their residential environment.

2.4. LOS Evaluation and 3D-Based Design

When applying robot-friendly design principles to the built environment, it is essential to quantify the level of comfort and circulation efficiency that arise when humans and robots coexist within the same spatial and temporal context. To address this issue, recent studies have proposed Level of Service (LOS) evaluation frameworks based on multi-agent systems that comprehensively consider both pedestrian movement patterns and the dynamic operational characteristics of robots, including turning radii, acceleration, and deceleration behaviors.

LOS serves as a key assessment concept for predicting the feasibility of human–robot coexistence through three principal dimensions: safety, operational efficiency, and positive user experience, such as minimizing unnecessary avoidance behaviors and circulation conflicts (Lee, 2025). In particular, LOS evaluation becomes a critical indicator in multi-housing environments, where interactions between humans and robots frequently occur within highly constrained spaces, such as narrow pilotis parking areas, shared corridors, and compact entrance zones.

Accurate assessment of robot-friendly LOS requires a three-dimensional planning and evaluation approach. Service robots perceive and map their surroundings using LiDAR and RGB-D cameras, which generate and process three-dimensional point cloud data representing the surrounding environment (Wang et al., 2023). Within this context, conventional two-dimensional drawings are inherently limited because they cannot adequately represent factors such as overhead protrusions, vertical obstacles, or abrupt floor-level changes that may cause perception errors during robot navigation. Consequently, architectural design must simultaneously consider the three-dimensional physical dimensions of robots and the spatial perception range of their sensing systems to ensure reliable and efficient operation (Lim et al., 2025).

2.5. Summary

The literature review indicates that technological advancements and demographic changes are driving the transformation of residential environments toward a new form of complex residential culture integrated with advanced infrastructure and smart services. However, multi-housing

Table 3. Certification Systems and Standards Related to Robot-Friendly Architecture

Region	Certification / Standard	Main Contents and Characteristics
South Korea	Robot-Friendly Building Certification (REEC)	Evaluation of architectural and facility design, network operation and management, and robot-supportive infrastructure
Japan	RFA Standard	Robot-friendliness levels for public and commercial facilities, including physical performance criteria and dimensional requirements
Singapore	Design for Maintainability Guide	Architectural requirements supporting robot operation, automation, and facility maintenance in residential and non-residential buildings

remain both physically and institutionally marginalized within this transition due to their inherent spatial constraints. As a result, the delivery systems for essential services, including logistics and caregiving, remain fragmented and insufficiently connected.

Furthermore, considering the three-dimensional spatial perception mechanisms of service robots, conventional design approaches based primarily on two-dimensional floor plans exhibit fundamental limitations in accommodating robotic mobility and operation. Therefore, there is a pressing need to establish 3D-based design guidelines capable of integrating public service infrastructure into multi-housing environments while simultaneously transforming existing residential culture. Such guidelines can provide the foundation for creating robot-friendly living environments that support safe and efficient human–robot coexistence and enable equitable access to advanced services regardless of residential building type.

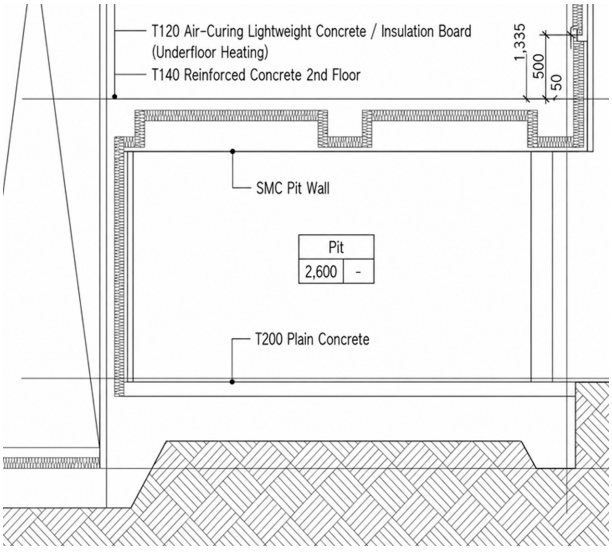


Figure 1. Cross-Sectional View Pilotis Parking Area.

3. Factors Limiting Robot Navigation in Multi-housing Areas

To ensure the practical applicability of the proposed design guidelines for service robot deployment, this study selected six multi-family and multi-dwelling residential buildings located in the Unjeong District of Paju City, Gyeonggi Province, as case study sites for analysis (Table 4).

Paju City has actively pursued smart city initiatives, particularly within the Unjeong District, through the implementation of smart urban development projects and the establishment of an integrated smart city platform. Consequently, the study area possesses strong potential for linkage with existing smart city demonstration infrastructure. Furthermore, the increasing number of single-person households has led to growing demand for multi-housing in the district, suggesting a corresponding increase in the demand for robot-based residential services.

3.1 Physical and Environmental Constraints in Shared Spaces

3.1.1. Dynamic Obstacles in Parking Areas and Entrance-Level Differences

In most multi-housing buildings, the ground floor is either directly connected to adjacent streets or utilized as a pilotis parking area, as illustrated in Figure 1. These spaces typically function as mixed pedestrian–vehicle circulation zones where pedestrian and vehicular movements are not physically separated. Consequently, irregularly parked vehicles act as large obstacles that obstruct the detection range of robots' LiDAR sensors. Pedestrians emerging unexpectedly from between parked vehicles can overload the dynamic obstacle-avoidance algorithms of service robots, significantly reducing navigation stability and operational reliability (Cha et al., 2025).

In addition, as shown in Figure 2, many residential buildings lack wheelchair-accessible ramps at their common entrances, while others contain steep stairways with gradients exceeding the navigational capabilities of service robots (approximately 5-8 degrees). Such conditions fundamentally prevent robots from accessing the building entrance and delivering services to residents.

Table 5 summarizes the conditions of parking facilities and common entrances observed in the analyzed case studies. The results indicate that most buildings employ a combination of pilotis parking and on-street parking arrangements. Furthermore, despite the presence of level differences at common entrances, ramps have generally not been installed, creating significant accessibility barriers for autonomous service robots.

Table 4. Case Study Buildings Selected for Analysis

Case	Building Type	Number of Floors	Units	Design Year
A	Detached House (Multi-family Housing)	B1 / 3 Stories Above Ground	5	2018
B	Detached House (Multi-family Housing)	3 Stories Above Ground	5	2019
C	Detached House (Multi-family Housing)	3 Stories Above Ground	5	2019
D	Detached House (Multi-family Housing)	3 Stories Above Ground	5	2019
E	Multi-household Residential Building	3 Stories Above Ground	4	2019
F	Multi-household Residential Building	3 Stories Above Ground	18	2019

Table 5. Existing Conditions of Parking Facilities and Common Entrances

Case	No. of Parking Spaces	Parking Type	Entrance Level Difference	Ramp Installation
A	5	Underground Parking	Present (+50 mm)	Not Installed
B	5	Pilotis + On-Street Parking	No Level Difference	Not Applicable
C	5	Pilotis Parking	Present (+100 mm)	Not Installed
D	5	Pilotis + On-Street Parking	Present (+100 mm)	Not Installed
E	4	Pilotis + On-Street Parking	No Level Difference	Not Applicable
F	18	Pilotis + On-Street Parking	Present (+370 mm)	Installed

Table 6. Existing Conditions of Elevators and Staircases

Case	Elevator Installation	Front Clearance Space	Stair Width	Landing Width
A	Installed	Secured	900 mm	900 mm
B	Not Installed	Not Applicable	1,180 mm	1,330 mm
C	Not Installed	Not Applicable	1,200 mm	1,300 mm
D	Not Installed	Not Applicable	1,200 mm	1,250 mm
E	Installed	Secured	1,200 mm	1,200 mm
F	Installed	Secured	1,200 mm	1,240 mm

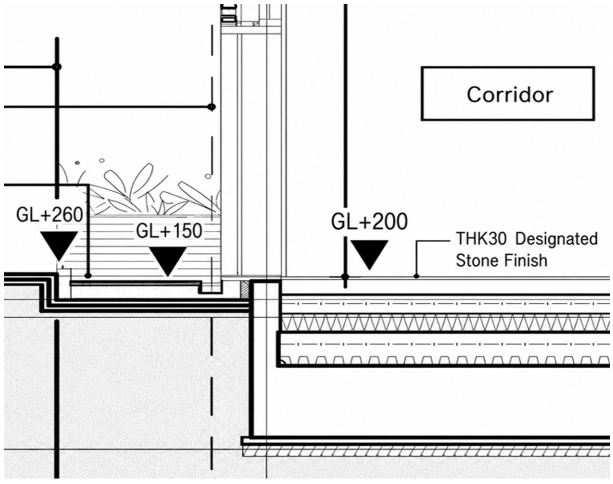


Figure 2. Detailed View of a Common Entrance.

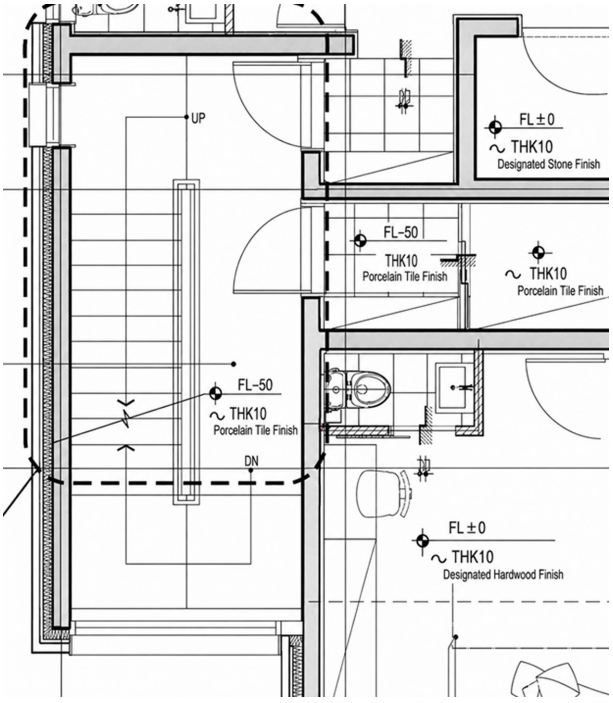


Figure 3. Partial Floor Plan of the Staircase Area.

3.1.2. Fundamental Absence of Vertical Mobility Systems and Narrow Staircases

Table 6 summarizes the elevator installations and staircase conditions observed in the analyzed case studies. In many multi-housing buildings, elevators are not installed due to financial limitations and floor area ratio constraints. As a result, wheeled delivery robots are fundamentally restricted from accessing residential units located on the second floor or above.

Even in buildings where elevators are provided, as illustrated in Figure 4, it is necessary to verify whether sufficient maneuvering space is secured in front of the elevator for robot operation. Furthermore, the shared staircases and corridors of multi-family and multi-dwelling housing are generally extremely narrow, with widths of approximately 1.2 m, while landing areas between floors are also highly constrained. Under such conditions, it becomes physically difficult or even impossible for robots to perform 180-degree turns or to pass pedestrians safely within the circulation space.

Third, the closed nature of building openings and the presence of communication blind spots on the ground floor present additional operational limitations. The common entrances on the first floor are typically designed with heavy manual swing glass doors, making autonomous

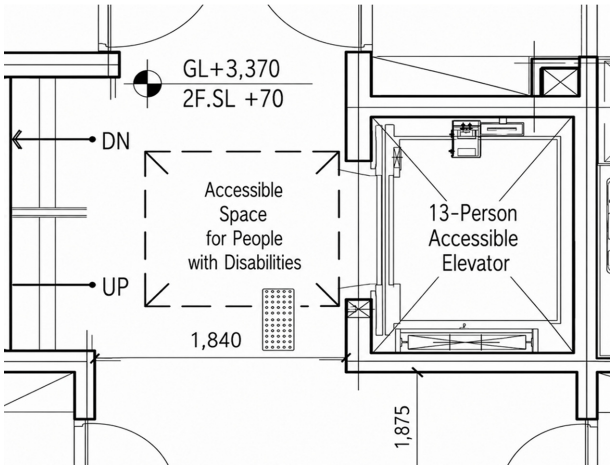


Figure 4. Partial Floor Plan of the Elevator Area.

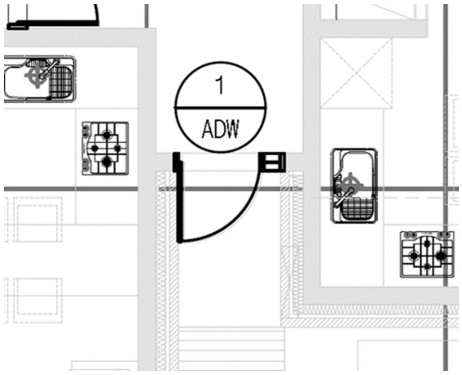


Figure 5. Ground Floor Window and Door Plan.

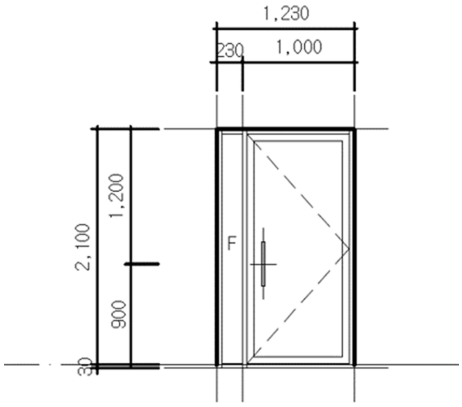


Figure 6. ADW1 Window and Door Schedule.

opening by service robots difficult. In particular, single-door entrance configurations without vestibules, combined with thick reinforced concrete bearing walls supporting the lower structure of the building, create severe communication blind spots between external communication networks and internal wireless systems (Lee, 2025).

As a result, communication failures may occur at critical moments when robots must interact with the building management server to obtain access authorization before entering the building. Such network interruptions can lead to a deadlock condition, in which robot navigation is permanently halted in front of the entrance. These issues are illustrated in Figure 5 and 6.

3.2. Structural and Behavioral Constraints in Private Residential Spaces

3.2.1. Risks Associated with Overcoming Entrance-Level Differences and Insufficient Vestibule Space

Due to the characteristics of Korea's traditional ondol floor-heating culture, residential unit entrances generally contain vertical level differences averaging approximately 50–150 mm in height in order to prevent dust and external contaminants from entering indoor spaces, as illustrated in Figure 7. When wheeled service robots attempt to overcome these level differences forcibly, there is a high risk of overturning caused by shifts in the center of gravity of loaded items, as well as potential damage to the lower drivetrain components of the robot.

Furthermore, multi-housing buildings generally possess highly constrained entrance vestibule spaces, as shown in Figure 8. These limited spatial conditions do not provide sufficient room for robots to generate the necessary propulsion force required to overcome entrance thresholds

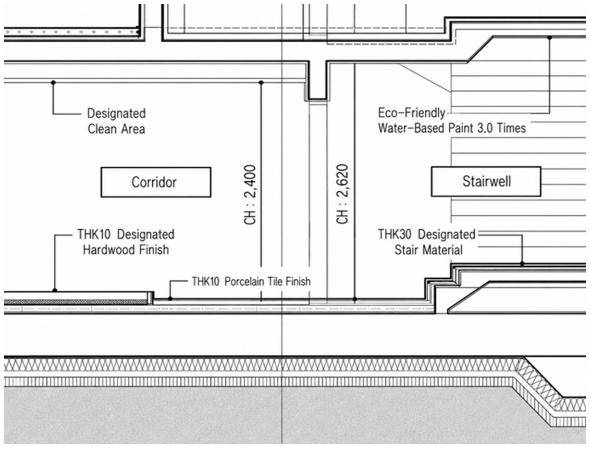


Figure 7. Cross-Sectional View of a Residential Unit Entrance.

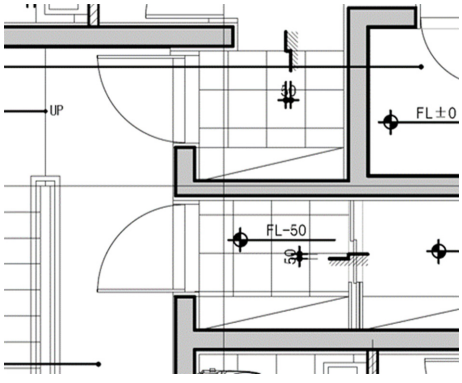


Figure 8. Floor Plan of a Residential Unit Entrance.

Table 7. Existing Conditions of Residential Unit Entrances

Case	Entrance Level Difference	Vestibule Dimensions	Ramp Installation
A	±0 mm	1.28 m × 1.36 m	Not Installed
B	+50 mm	1.0 m × 1.5 m	Not Installed
C	+70 mm	1.2 m × 1.5 m	Not Installed
D	+70 mm	1.15 m × 1.2 m	Not Installed
E	+80 mm	1.2 m × 1.5 m	Not Installed
F	+80mm	1.15m × 1.5m	Not Installed

or to perform directional adjustments and turning maneuvers safely.

Table 7 summarizes the level differences, vestibule dimensions, and ramp installation conditions observed at the entrances of each residential unit.

3.2.2. Optical Noise and Non-Uniformity of Finishing Materials

Interior door thresholds with heights ranging from approximately 30-50 mm function as physical obstacles that interrupt the continuous movement of service robots. In addition, glossy polishing tiles and metallic moldings, which are frequently used in multi-housing remodeling projects to create the visual impression of larger spaces, generate strong light reflections that can reflect or distort the laser beams emitted by LiDAR sensors (Lim et al., 2025). Visual sensors are also highly vulnerable to intense backlighting entering through windows and glare generated by artificial lighting systems, which may temporarily impair perception performance and cause recognition errors (Seo et al., 2025).

Furthermore, lifting and deformation of low-cost vinyl flooring materials can induce wheel slippage, resulting in the continuous accumulation of positioning errors within wheel-odometry-based localization systems.

3.2.3. Interference Between Multiple Robots in Narrow Residential Spaces

Within compact residential units ranging from approximately 30-60 m+, the presence of furniture and structural bearing walls frequently reduces effective corridor widths to less than 800 mm. Under these constrained spatial conditions, simultaneous movement by residents and robots significantly reduces the available avoidance clearance, leading to a severe decline in the Level of Service (LOS) between humans and robots (Lee, 2025).

Frequent circulation interference forces robots to repeatedly recalculate navigation paths, thereby reducing operational efficiency and, in extreme cases, causing robots to stop entirely due to continuous pathfinding conflicts.

3.3. Identification of Key Factors Limiting Robot Navigation

Based on the analysis of the spatial characteristics of multi-housing and the operational characteristics of service robots, the principal factors limiting the establishment of robot-friendly environments can be summarized into three categories.

First, there is the issue of geometric discontinuity. Existing architectural configurations based on vertical circulation systems, including entrances without ramps, staircases without elevators, and elevated interior thresholds, fundamentally interrupt the continuous movement of wheeled robots (Park et al., 2025).

Second, there are perceptual blind spots. Architectural elements such as pilotis columns and narrow corridor corners obstruct the sensing range of robotic systems, making real-time responses to dynamic obstacles difficult. In particular, negative floor-level differences that cannot be detected by downward-facing sensors are a major cause of fall-related accidents (Wang et al., 2023).

Third, there is a lack of functional buffer space. Due to the limited dimensions of both private and shared residential areas, it is physically difficult to secure sufficient buffer zones for robot waiting, charging, and safe human–robot interaction and passing movements (Kim et al., 2023).

These limitations cannot be resolved solely through dimensional improvements in two-dimensional floor plans. Instead, comprehensive three-dimensional design interventions that consider the volumetric movement and perceptual range of robots are essential.

4. Proposal of 3d-based Design Guidlines

4.1. Fundamental Principles of the Proposed Guidelines

To overcome the identified limitations affecting robot navigation, this study proposes three fundamental principles for robot-friendly design in multi-housing environments.

First, geometric form modifications and minimal small-scale lift infrastructure should be introduced to reconnect the vertically and horizontally fragmented circulation routes caused by stairs and level differences. Second, the three-dimensional physical dimensions of robots and the limitations of their sensor viewing angles should be structurally supplemented to eliminate sensor blind spots and prevent falls and collision accidents. Third, considering the spatial constraints of multi-housing buildings, idle and underutilized spaces should be strategically employed to provide robot waiting and pickup areas without infringing upon residents' living and circulation spaces.

4.2. Design Guidelines for Shared Spaces

4.2.1. Establishment of a "Robot Delivery Hub Station" within Ground-Floor Pilotis Areas

In buildings where the installation of new elevators is spatially impractical, this study proposes the installation of an unmanned robot delivery storage system (Hub-Station) within residual spaces of ground-floor pilotis parking areas or common entrance lobbies to prevent delivery robots from navigating steep stairways.

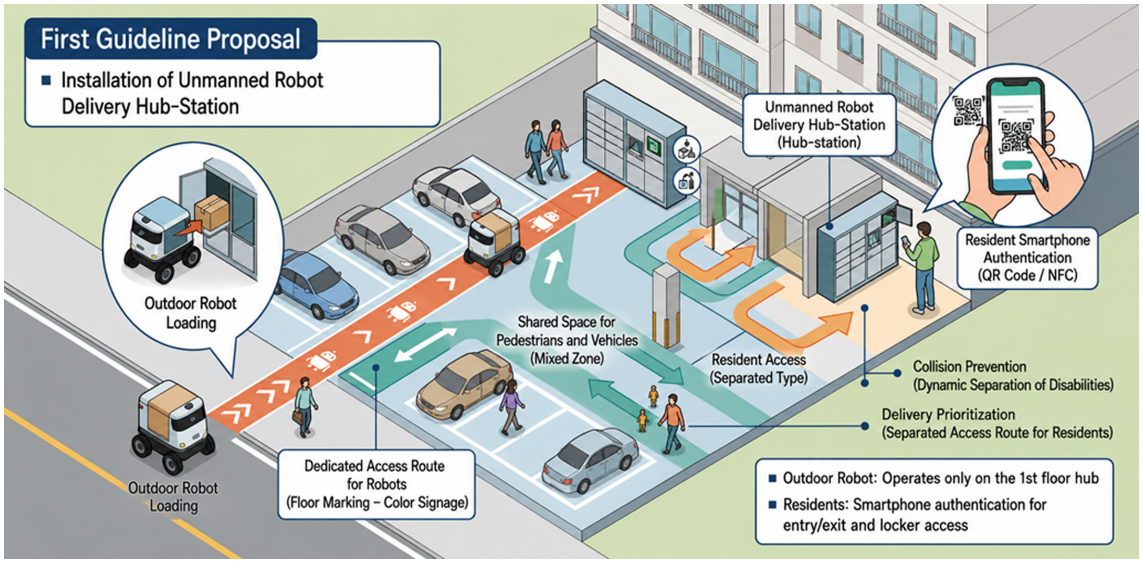


Figure 9. Conceptual Diagram of a Robot Delivery Hub Station in a Pilotis Space (Generated Using AI).

Under this system, external delivery robots would access only the first-floor storage station to deposit parcels before returning to their service routes, while residents would retrieve their deliveries through smartphone-linked access systems during entry or departure from the building. This approach establishes a separated circulation system between robots and residents.

Furthermore, within pilotis parking areas where pedestrian and vehicular circulation are mixed, robot-exclusive access routes should be visually distinguished through floor markings and guidance systems to prevent collisions with dynamic obstacles such as vehicles and pedestrians (Figure 9).

4.2.2. Installation of Robot-Exclusive Lifts for Overcoming Vertical Mobility Limitations

To fundamentally address the limitation of first-floor hub stations—namely, the inability to provide direct delivery to individual residential units—this study proposes the installation of robot-exclusive small elevators (dumbwaiter-type lifts). Since existing multi-housing buildings generally lack sufficient interior space, these lifts may be constructed as either external or internal additions by utilizing residual spaces along building façades or within staircase cores.

Compared to conventional passenger elevators, these compact lift systems can significantly reduce installation

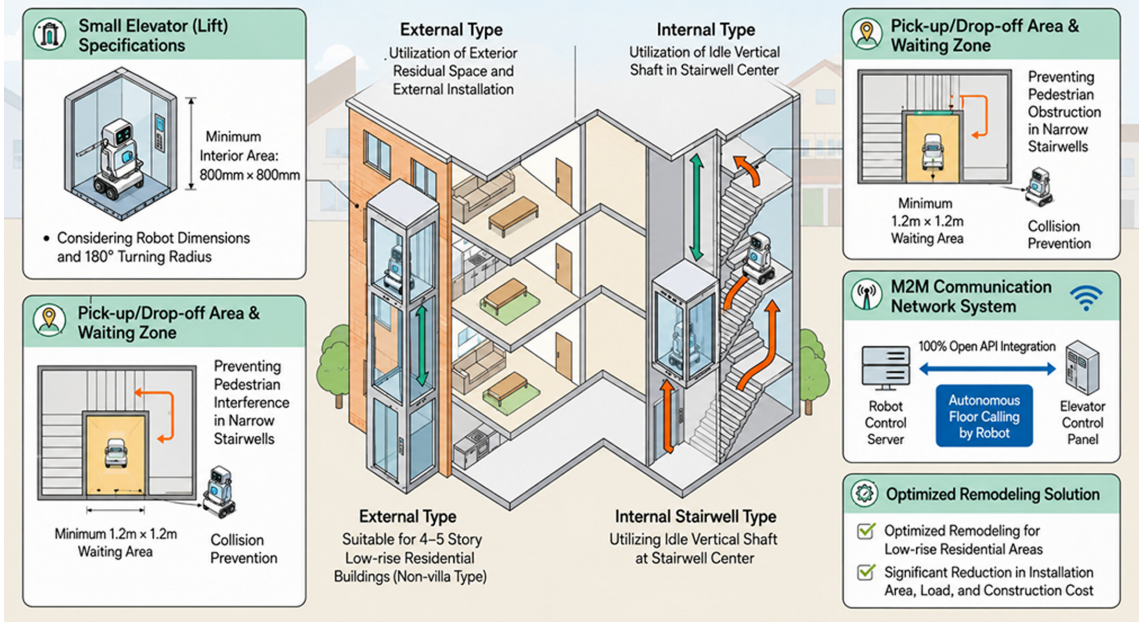


Figure 10. Conceptual Diagram of a Robot-Exclusive Lift System for Vertical Mobility (Generated Using AI).

area requirements, structural loading, and construction costs. Considering the physical dimensions and 180-degree turning radius of delivery robots, the lift cabin should secure a minimum internal operating area of 800 mm × 800 mm. In addition, a network system based on Open API communication between the robot control server and the elevator control panel should be established so that robots can autonomously call and operate the lift system during delivery operations (Figure 10).

4.2.3. Barrier-Free Access Routes and Network-Integrated Openings

To ensure stable access to first-floor robot hub stations or small lift systems, existing steep stairways should either be removed or bypassed through the installation of dedicated robot ramps with a minimum effective width of 900 mm and a slope ratio not exceeding 1:18.

To prevent sensor distortion caused by diffuse reflections from direct sunlight, low-reflectivity finishing materials such as matte tiles should be applied to ramps and lobby entrance areas. Furthermore, conventional first-floor entrance doors should be completely replaced with network-integrated automatic sliding doors directly connected to the robot communication server. This system enables automatic door operation upon robot approach, thereby fundamentally eliminating congestion and access bottlenecks at building entrances (Figure 11).

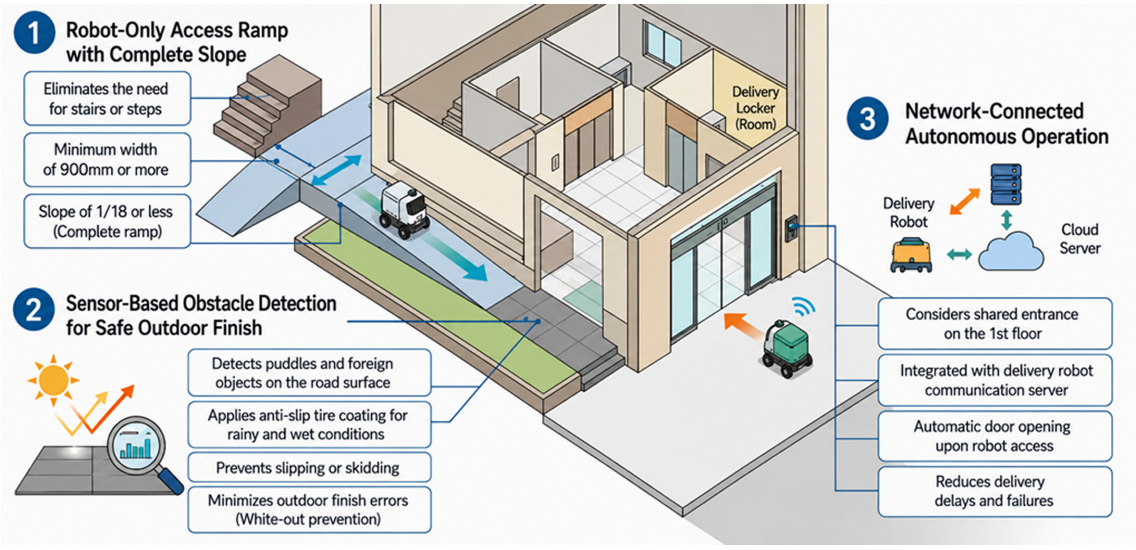


Figure 11. Conceptual Diagram of Barrier-Free Access and Network-Integrated Entrance Systems (Generated Using AI).

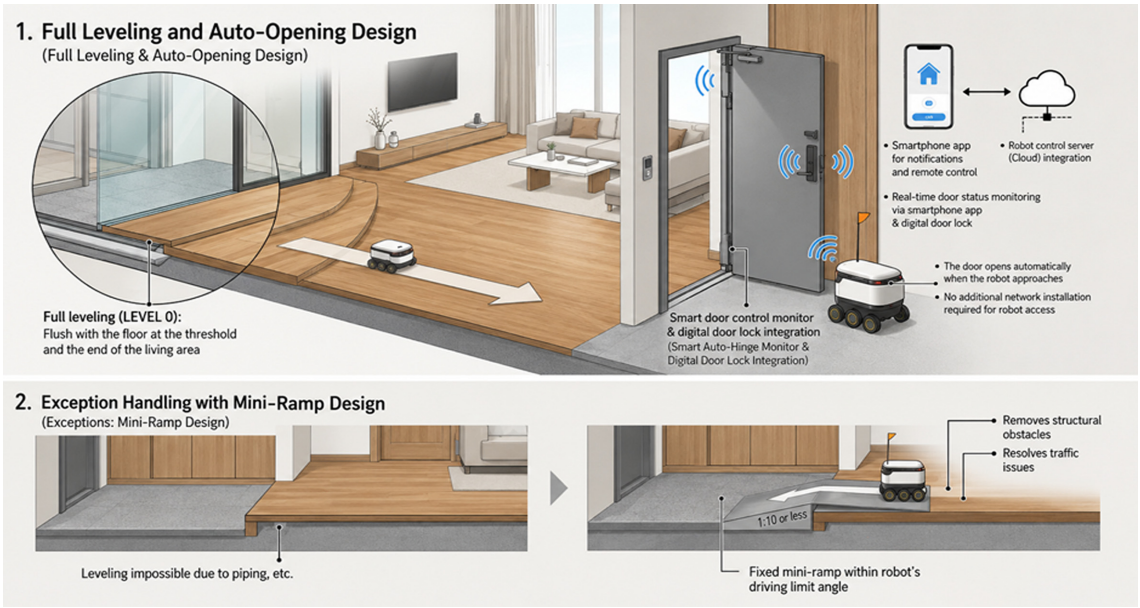


Figure 12. Conceptual Diagram of Entrance-Level Mitigation and IoT-Integrated Access Systems (Generated Using AI).

4.3 Design Guidelines for Private Residential Spaces

Unlike delivery robots, indoor care and domestic assistance robots continuously coexist with residents within private living environments. Therefore, advanced design strategies are required to ensure efficient utilization of limited residential areas while maintaining both the psychological and physical comfort of residents.

4.3.1. Mitigation of Entrance-Level Differences and IoT-Integrated Openings

During remodeling processes, the level of entrance flooring and living room flooring should be fully aligned to achieve a completely barrier-free floor condition, thereby permanently eliminating entrance obstacles for robotic movement.

If complete leveling is infeasible due to plumbing or structural constraints, fixed mini-ramps designed within the allowable climbing angle of service robots should be installed to ensure stable movement. In addition, fire doors should integrate smart auto-hinge motors and digital door-lock systems wirelessly connected to smartphones and robot control servers, enabling automatic opening and closing when robots approach through a smart-home network system (Figure 12).

4.3.2. Application of Sensor-Friendly Finishing Materials and Removal of Interior Thresholds

Interior thresholds between living rooms and bedrooms should be removed to ensure uninterrupted robot movement. To prevent sensor reflection errors and wheel slippage during navigation, interior flooring materials should consist of a continuous, non-glossy matte surface with a consistent coefficient of friction extending seamlessly from the living room into each bedroom.

In addition, lighting-control devices such as roller screens should be installed to minimize glare and backlighting caused by windows and interior lighting systems, which may negatively affect robotic vision sensors. Indoor lighting environments should also maintain consistent color temperature and color-rendering properties to ensure stable visual recognition performance (Figure 13).

4.3.3. Zoning Strategies and Docking Stations for Preventing Human–Robot Interference

To prevent collisions between humans and robots within the constrained interiors of multi-housing units, large furniture elements such as sofas and storage systems should be arranged to maintain clear visibility and sufficient clearance near corners and circulation intersections.

In particular, docking stations used for robot charging and standby functions should not protrude into circulation pathways or obstruct pedestrian movement. Instead, these systems should be integrated into built-in configurations utilizing residual wall cavities within corridors or lower spaces beneath living-room cabinetry. Such integrated design strategies can simultaneously enhance operational functionality and spatial aesthetics (Figure 14).

5. Proposal of A Prototype Applying the Design Guidelines

5.1. Derivation of Prototype Requirements

To implement the previously proposed 3D-based design guidelines within actual architectural environments, this study derived three prototype requirements to examine their geometric feasibility.

First, the effective circulation width and three-dimensional maneuvering space must be defined. Spatial dimensions within

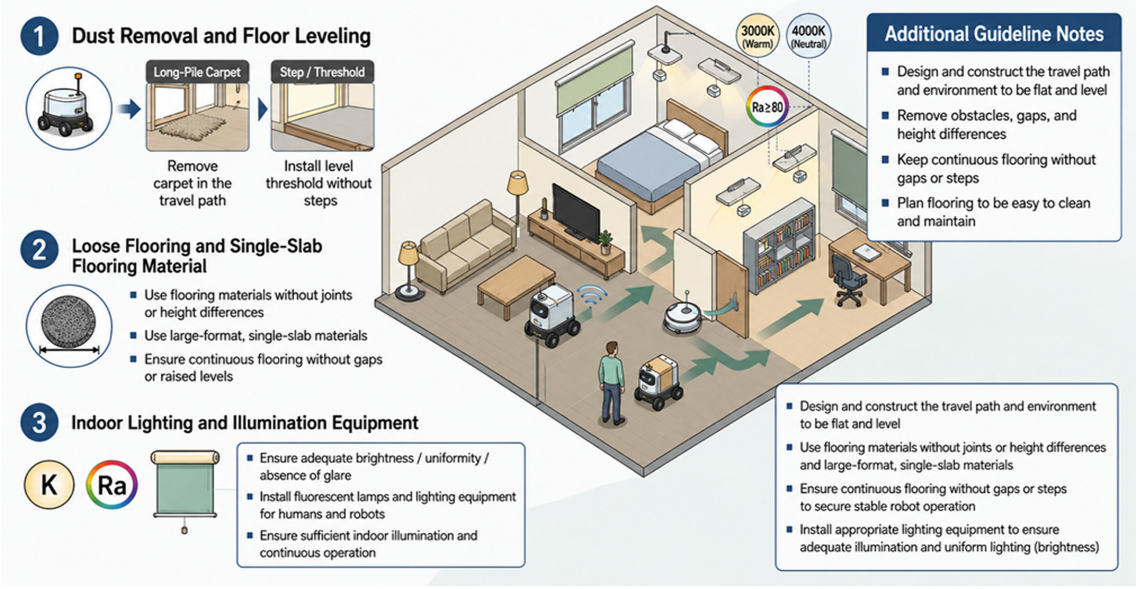


Figure 13. Conceptual Diagram of Sensor-Friendly Finishing Materials and Threshold Removal (Generated Using AI).

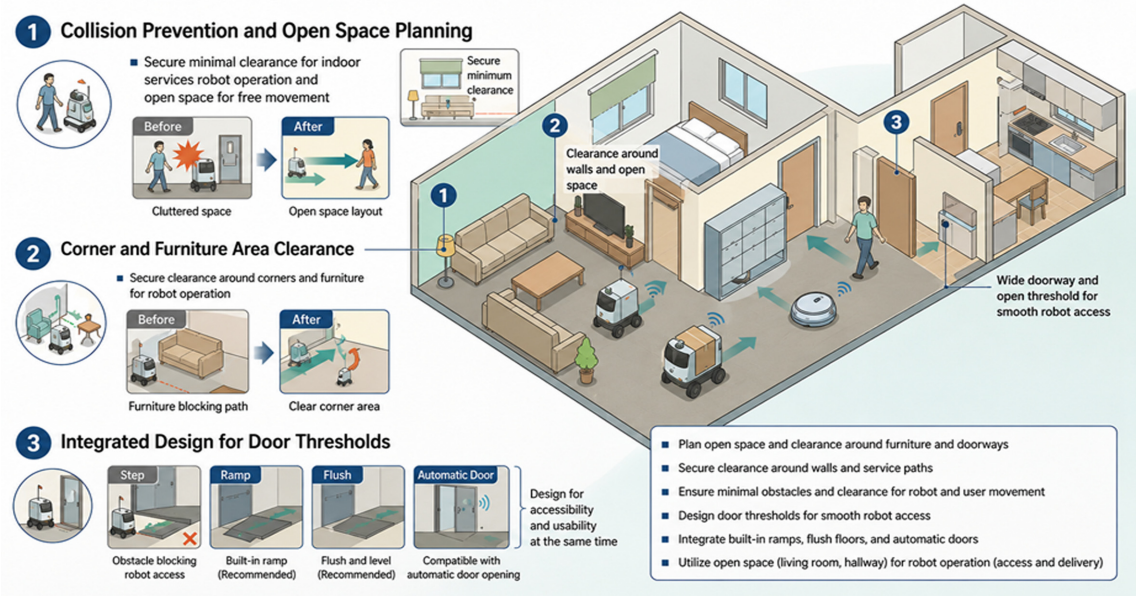


Figure 14. Conceptual Diagram of Interference-Prevention Zoning and Built-In Docking Stations (Generated Using AI).

the 3D model should be established to accommodate the physical volume and operational movement of service robots.

Second, physical supplementation of the information-recognition environment is required. Architectural elements that generate sensor blind spots for robots should be identified and geometrically modified. In particular, object designs that improve sensor readability—such as introducing visual inflection points at floor-level boundaries—should be considered.

Third, architectural objects ensuring geometric continuity should be modularized. The geometric forms of architectural elements connecting fragmented vertical circulation routes and thresholds must be defined and modularized. Independent architectural components, including the curvature of barrier-free ramps and the depth of alcove-type buffer spaces, should be designed as flexible modules that can be combined according to spatial requirements.

5.2. Prototype Production and Application

Based on the derived requirements, a robot-friendly prototype model was produced and applied using a general-purpose 3D modeling program for a case study involving a four-story multi-dwelling residential building.

5.2.1. Modification of the Entrance Route

The existing common entrance originally contained a 50 mm level difference between the ground surface and the first-floor slab, creating limitations for robot navigation. To resolve this issue, a ramp satisfying a slope ratio of less than 1:18 was installed along the entrance route to eliminate the level difference (Figures 15 and 16).

Furthermore, considering both the pilotis parking area

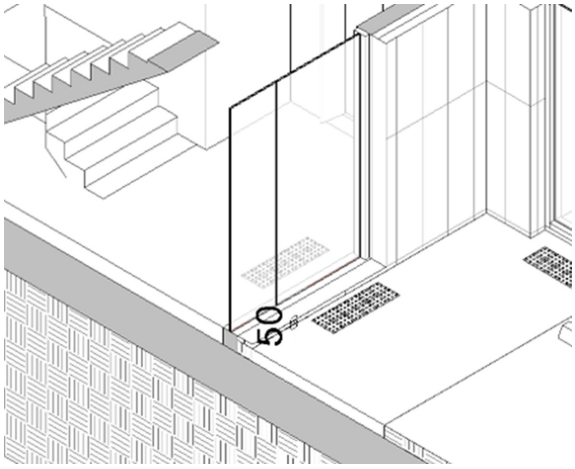


Figure 15. Existing Condition Before Removal of the Level Difference.

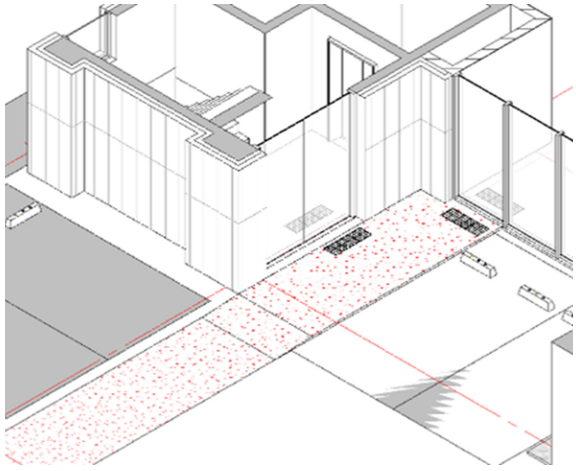


Figure 16. Installation of the Access Ramp.

and pedestrian access routes on the ground floor, a dedicated delivery robot circulation path was established. Distinct floor-finishing materials were applied to visually separate the robot pathway and enhance recognition by robotic sensors.

5.2.2. Drop-Off Zone

A drop-off zone may be established within residual spaces on the first floor. In the analyzed case study, the ground floor already contained both a pilotis parking area and neighborhood commercial facilities, allowing part of the commercial space to be converted into a robot drop-off zone. However, in many multi-housing buildings, the lack of available residual space may restrict the installation of separate drop-off facilities (Figure 17).

When installation of a drop-off zone on the ground floor is spatially infeasible, delivery storage boxes may instead be installed within dead spaces beneath staircases. In addition, if the building core and upper structural conditions permit, a robot-exclusive vertical lift may be installed along the exterior façade to provide direct delivery services to residential units (Figure 18).

5.2.3. Removal of Interior Level Differences and Application of Embedded Linear Trenches

At the residential unit entrance, ramps were installed to resolve the spatial discontinuity between shared spaces and private residential areas. Considering the limited interior dimensions, the ramp gradient was designed to remain below 1:12 (Figure 19).

Within bathrooms, floor finishing levels were adjusted to eliminate level differences. To prevent water overflow resulting from threshold removal, embedded linear trench drains were installed at the locations where existing thresholds had previously been positioned (Figure 20).

5.2.4. Securing Alcove-Type Buffer Spaces

Within residential units, narrow corridors with widths

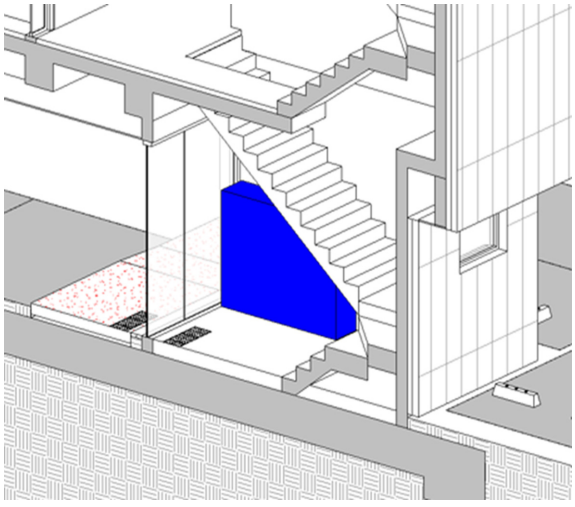


Figure 17. Installation of a Drop-Off Zone.

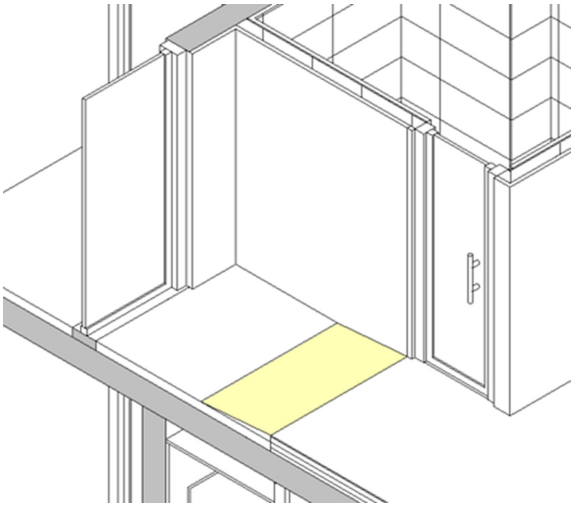


Figure 19. Installation of an Interior Ramp.

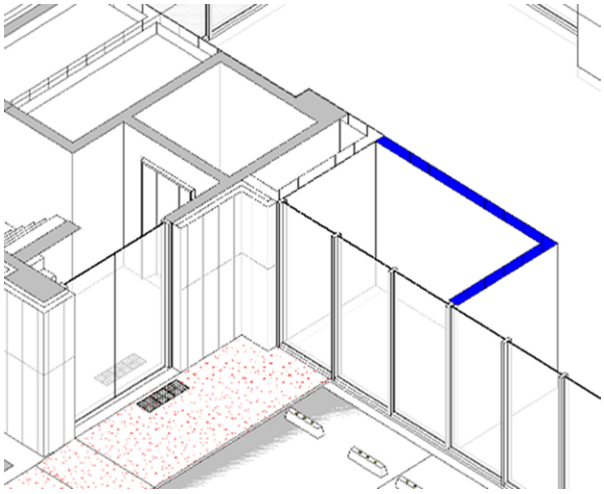


Figure 18. Utilization of Under-Stair Dead Space.

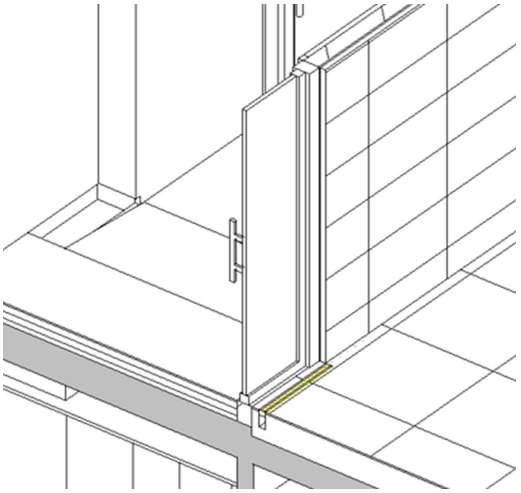


Figure 20. Removal of Bathroom Level Differences.

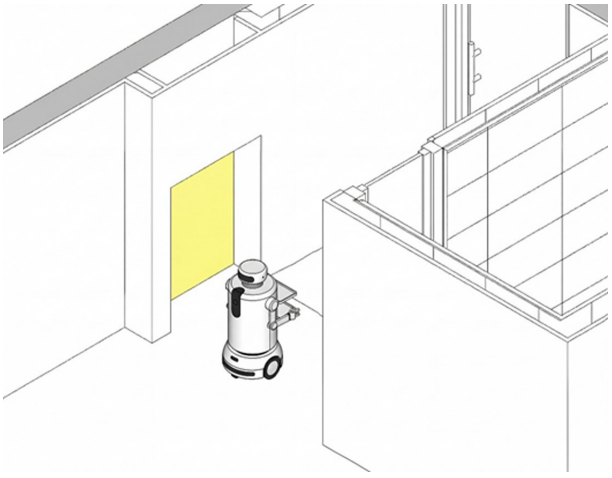


Figure 21. Alcove-Type Space Within Residential Units.

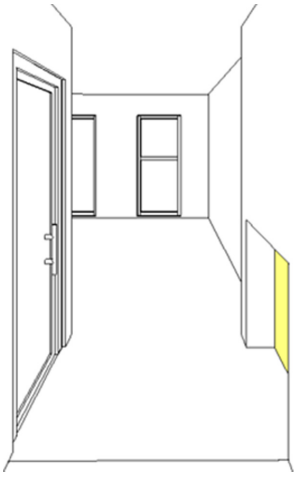


Figure 22. Residential Corridor with Alcove-Type Buffer Space.

below 1.2 m, combined with furniture placement, create limitations for simultaneous circulation by humans and robots. To address this issue, wall surfaces were setback by approximately 300 mm to create alcove-type buffer spaces (Figure 21).

These alcove-type buffer spaces also contribute to maintaining visual continuity and spatial consistency within the residential environment (Figure 22).

The process of producing and applying these architectural-object-centered 3D prototypes enables intuitive evaluation of how architectural form transformations influence robot navigation stability and perceptual reliability without requiring complex robotic algorithm simulations. Consequently, the proposed approach may serve as a standard model for future environmental improvements in multi-housing areas within 3D design and BIM-based environments.

6. Conclusions

This study proposed integrated 3D-based design guidelines that combine autonomous robot navigation systems with public service infrastructure to address the issues of physical disconnection and service marginalization within multi-housing areas, which represent one of the most common housing types in contemporary society amid rapid population aging and the increasing prevalence of single-person households.

Through analyses of existing multi-family and multi-dwelling housing cases, the study identified key environmental factors hindering robot navigation, including level differences and narrow corridor widths. Based on these findings, three principal design principles grounded in safety, accessibility, and integrated cultural connectivity were established. In particular, the study confirmed that morphological transformations of architectural objects can enable residential spaces to function as nodes of public service infrastructure, thereby establishing a physical foundation for a complex residential culture in which technology and space are organically integrated.

The significance of this study lies not merely in the introduction of robotic technologies, but in the proposal of robot-friendly architectural guidelines capable of creating new cultural and spatial values for multi-housing areas through the integration of advanced infrastructure and public services.

However, this study is limited in that its scope was confined to the establishment of design guidelines and the proposal of prototype models. Consequently, dynamic navigation simulations involving virtual robot agents within digital environments were not conducted. Therefore, future studies should apply the proposed guidelines within simulation-based environments and conduct quantitative validation—including navigation performance evaluation and line-of-sight analysis—through ROS (Robot Operating System)-based physical simulations to further advance and refine the proposed guidelines.

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