Planning and Design Methods for Robot Work spaces in Smart Elderly Care Communities

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Abstract
The global aging problem is becoming increasingly severe, and the innovative application of robotics technology has emerged as a key driver for upgrading the elderly care industry. In the face of the dual challenges of accelerating global population aging and the surging demand for elderly care services, how to rapidly and effectively integrate robotics into elder care has become an urgent issue. This study innovatively proposes transforming complex robotic operational requirements into three-dimensional architectural spatial models by analyzing the dimensional and motion space needs of eldercare robots in community environments. Through in-depth analysis of the functions, dimensions, movement angles, and ranges of eldercare robots, combined with spatial layout principles from architecture and urban planning, the study constructs a tangible model of the workspace requirements for robots. And starting from the six tasks of caring for the elderly, the key points of design and planning for bedrooms, living rooms and bathrooms based on the needs of care robots in architectural space are proposed.This approach not only ensures sufficient mobility for robots to perform various tasks but also enhances their operational efficiency and safety within elderly care communities. It opens new pathways for the precise renovation and optimisation of smart elderly care communities, driving deeper integration between technology and daily living.

Keywords: Smart elderly care community, robots, spatial planning, spatial design, elderly care space

Introduction

Amid the rise of smart eldercare, the innovative application of robotic technology has become a key driving force in upgrading the eldercare industry. Confronted with the dual challenges of a rapidly aging population and the surging demand for eldercare services in China, how to enable robotic technology to effectively support and care for the elderly has emerged as an urgent issue. In January 2024, the Opinions of the General Office of the State Council on Developing the Silver Economy to Enhance the Well-being of the Elderly explicitly stated the need to foster new models of smart healthcare and eldercare, and to promote the integrated application of intelligent nursing robots, household service robots, and other devices across home-based, community-based, and institutional eldercare settings [1]. Subsequently, in June 2024, the Shanghai Action Plan for the Innovative Development of Eldercare Technology (2024–2027) further emphasised the importance of accelerating the development of smart eldercare technology communities and advancing age-friendly home modifications. In particular, the plan highlights the application of advanced health equipment such as rehabilitation devices, exoskeletons, and nursing robots, and underscores the crucial role of technology in improving the quality of life for older adults [2]. As a vanguard in the smart eldercare domain, robots are increasingly becoming a critical force in enhancing the living standards of the elderly and advancing the development of smart eldercare communities.

Currently, eldercare robots primarily fall into three categories: rehabilitation robots, domestic service robots, and social companion robots [3]. Existing research mainly focuses on technological dimensions, such as human–robot interaction and social engagement, perception and navigation systems, as well as rehabilitation and health monitoring [4]. While each type of eldercare robot features unique design characteristics, studies examining their practical deployment within smart eldercare environments remain limited. Moreover, their physical dimensions are often constrained by a combination of technical feasibility, functional requirements, and safety considerations, making it difficult for them to achieve the same level of flexibility and spatial adaptability as human caregivers. As shown in Figure 1, the extended reach of BUSBOY's remote manipulation arms, the robust support structure of ROBEAR, the wheeled chassis of Stardust Intelligence, and the bipedal humanoid design by Unitree Robotics all demonstrate impressive technological advancements. However, they also underscore the diversity and challenges in robot size and movement range. In various eldercare settings—including home, community, and institutional environments—different robot morphologies (e.g., bipedal humanoid, wheeled, tracked) may face limitations in terms of spatial compatibility, which can hinder service efficiency and negatively affect user experience. Therefore, it is imperative to adopt architectural approaches to assess and optimise care environments, ensuring the seamless integration of eldercare robots with diverse dimensions and forms into homes, communities, and eldercare institutions.

The age-friendly transformation of smart communities is, in essence, a bidirectional process of empowerment between technology and spatial design. The integration of these two dimensions enables the creation of intelligent eldercare scenarios, thereby enhancing the well-being and sense of fulfillment of older adults in the digital age [5]. At present, research on age-friendly residential design is relatively extensive, encompassing psychological and physiological needs of the elderly [6], barrier-free design principles [7], and smart home systems [8], among other topics. However, current community retrofitting efforts remain largely centered on the needs of older adults, with insufficient attention paid to the operational characteristics and spatial requirements of service robots. Existing studies related to the application of eldercare technologies are mainly focused on regulating the physical environment of residential buildings and monitoring the safety of older individuals [9], while research on the spatial integration of eldercare robots into residential settings is still in its infancy. To ensure that robots become effective assistants in the daily lives of older adults—rather than spatial obstacles—it is necessary to undertake a comprehensive restructuring and functional upgrading of home environments. The key research challenges are twofold: first, how to incorporate the operational characteristics and spatial demands of robots into the core of a human-centered design framework; and second, how to overcome the inefficiencies of in-situ adaptation testing by leveraging spatial modeling technologies to conduct multi-scenario simulation analyses. Such an approach can support and guide the precise transformation and optimisation of smart communities and residential spaces.

In the field of robotic modeling and simulation, advanced platforms such as Gazebo and V-REP provide researchers with powerful virtual testing environments, enabling preliminary validation of robotic system performance and adaptability without direct interaction with physical hardware. However, when applied to the specific context of eldercare communities, the widespread adoption of such tools faces notable limitations. While these platforms excel at simulating robotic dynamics, sensor integration, and complex interactions, they present significant challenges in accurately reconstructing the architectural nuances of real-world living environments—particularly with respect to furniture arrangements, soft furnishings, and the personalised characteristics of residential spaces. Given the complexity and variability of eldercare community environments, relying solely on robotics-focused simulation tools often fails to capture the fine-grained spatial distinctions that directly affect robotic navigation, task performance efficiency, and operational safety. Therefore, from an architectural perspective, it is essential to translate the functional requirements of eldercare robots into a design-oriented vocabulary and conduct in-depth spatial modeling and simulation tailored to residential care scenarios. This architectural reframing represents a critical bottleneck to be addressed in order to facilitate the effective deployment and integration of robotic technologies within eldercare communities.

The research objective of this paper is to optimize the layout of the home environment through scientific and reasonable spatial planning, enabling robots to operate freely under different spatial dimensions and activity angles, and meeting the diversified needs of the elderly. By analyzing the motion characteristics, working range and spatial requirements of robots, combined with the spatial layout principles of architecture, it is possible to create elderly care communities that not only conform to the operation norms of robots but also take into account the quality of life of the elderly. On this basis, by using advanced modeling and simulation technology, the potential obstacle areas are accurately marked, the working paths and activity Spaces of the robots are optimized, and the design key points of the three areas of the bedroom, bathroom and living room based on six nursing tasks are proposed. Ensure that the robot can seamlessly integrate into the environment of the elderly care community during actual deployment to achieve efficient, safe and humanized services.

2. Methodology

2.1 Research Subjects

Eldercare Robots:This study focuses on general-purpose eldercare robots that are either currently available in the market or under active development in research laboratories. These robots typically possess functions such as care-giving, companionship, and health monitoring, and are designed to assist older adults with daily living tasks in residential environments. The research will examine the spatial requirements, behavioral patterns, and environmental interactions of these robots during actual operations, with an emphasis on how their physical and functional characteristics influence their performance within domestic settings.

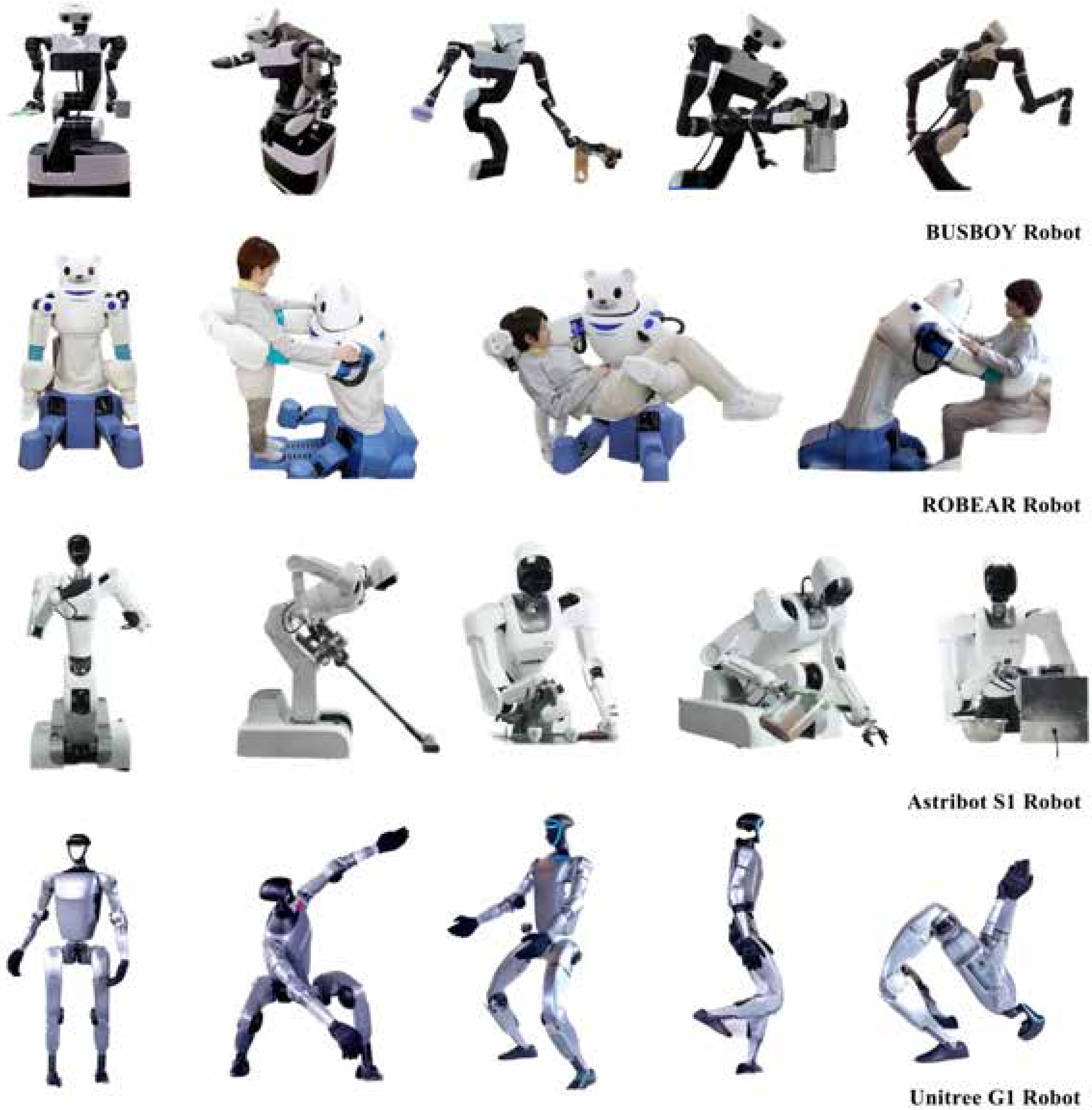
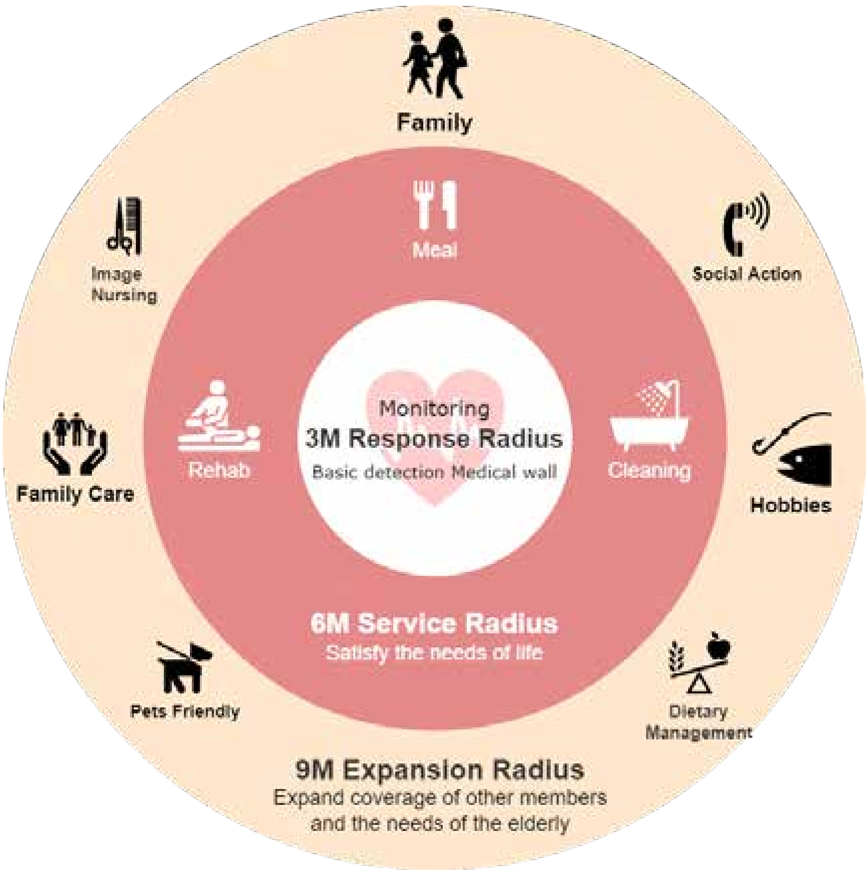


Figure 1. Display of various forms and motion ranges of the nursing robot

Residential Spaces in Smart Eldercare Communities:The study also targets the spatial layout and functional configuration of residential units within smart eldercare communities. Particular attention is given to analyzing how existing residential configurations—such as room layouts, furniture arrangements, and corridor designs—can be adapted or optimised to accommodate the integration of eldercare robots.In the elderly care scenario, nursing robots mainly undertake six key auxiliary tasks, namely: feeding, pushing wheelchairs, assisting with getting in and out of bed, helping with dressing, assisting with bathing and using the toilet. Ensuring that robots can operate efficiently and unobstructedly within these environments, while also supporting the daily needs of elderly residents, is critical for achieving seamless human-robot coexistence. In the design of smart eldercare communities, spatial planning must prioritise adequate mobility space for robots and prevent furniture from becoming obstacles to their movement. The introduction of robots imposes new spatial demands, including the allocation of walking paths, the establishment of interaction zones, and the assurance of universal accessibility. These spatial modifications must simultaneously address the physical and psychological needs of older adults and align with the dimensional and operational requirements of robotic systems.



2.2 Research Methodology

To accurately simulate and optimise the deployment and operational scenarios of eldercare robots with varying dimensions in smart eldercare communities, this study proposes a systematic methodology consisting of three core stages:

(1) Spatial Requirements Analysis and Robot Model Reconstruction:The study begins with an in-depth analysis of the functions, dimensions, and operational ranges of eldercare robots. Utilising robotic kinematics, key actions such as arm lifting, body rotation, and object manipulation are examined to determine the spatial footprint associated with daily tasks. By precisely measuring and simulating the trajectories of these movements, a three-dimensional entity model of the robot is constructed, effectively translating its operational space requirements into physical forms. Through virtual simulations, these models are used to replicate the robot's motion within residential environments, allowing early identification and resolution of potential spatial conflicts.

(2) Path Verification and Charging Zone Selection:In conjunction with SLAM (Simultaneous Localisation and Mapping) technology, the study investigates robot navigation paths within residential spaces to ensure unobstructed mobility—particularly in narrow corridors, doorways, and densely furnished areas. SLAM enables the real-time generation of environmental maps and supports path planning and obstacle avoidance algorithms, thereby ensuring that robots can complete tasks safely and efficiently in complex settings. Additionally, path optimisation algorithms are applied to analyze and select suitable locations for charging stations, ensuring robots can reliably return for charging without disrupting the daily routines of elderly residents. This technical framework provides scientific support for spatial layout and path planning tailored to robotic operations.

(3) Space, Furniture, and Soft Furnishing Validation Based on Task Simulation:A combined application of Sketch Up and Unity is used to conduct three-dimensional reconstructions of eldercare environments and to simulate robot adaptability. Sketch Up is utilised to build precise residential space models, into which dynamic robot models are embedded to assess spatial adaptability and predict potential obstacles. Unity is employed to simulate robot–furniture interactions, optimise path planning, and enhance task efficiency and operational safety. Furthermore, personalised validation of soft furnishing elements is conducted to ensure they align with the preferences of elderly users while avoiding interference with robotic operation. This process integrates principles from environmental behavior studies to identify suitable soft furnishing configurations that support harmonious human–robot coexistence. Ultimately, simulation results inform spatial optimisation strategies that facilitate the seamless integration of robots into eldercare environments, while simultaneously meeting the everyday needs of older adults—achieving a deep fusion of technology and daily life.

3.Case Study

3.1 Multi-Scenario Spatial Demand Analysis and Dynamic Model Construction for Eldercare Robots

An in-depth analysis was conducted on the functions, dimensions, and movement angles and ranges of eldercare robots to determine the spatial requirements for performing various tasks within elderly residential environments. Employing robotic kinematic analysis methods, this study examined key operational actions—such as assisting elderly individuals in standing or walking, performing household chores, and pushing wheelchairs—across a range of common care-giving scenarios. By precisely measuring and simulating the motion trajectories of these actions, the required spatial envelope and joint movement angles for each task were accurately derived.

The research focused on mapping the task-specific operational needs of eldercare robots across different residential settings. For each scenario, the robot's primary tasks were defined based on the functional zones of the living space. Corresponding motion postures and spatial operation strategies were then carefully designed to accommodate these tasks. Given the high spatial precision required for robotic flexibility, stability, and accuracy in residential settings, three-dimensional entity models of the robots were constructed based on measured data to convert operational requirements into physical spatial representations (Figure 2). By translating task motions into spatial forms, these models enable realistic simulation of robotic trajectories and workspace coverage in virtual environments.

The construction of robot entity models not only facilitates precise residential space planning but also allows for the early detection and resolution of potential spatial conflicts through virtual simulation. This modeling process lays the foundation for creating living environments that accommodate robotic assistance effectively and harmoniously.

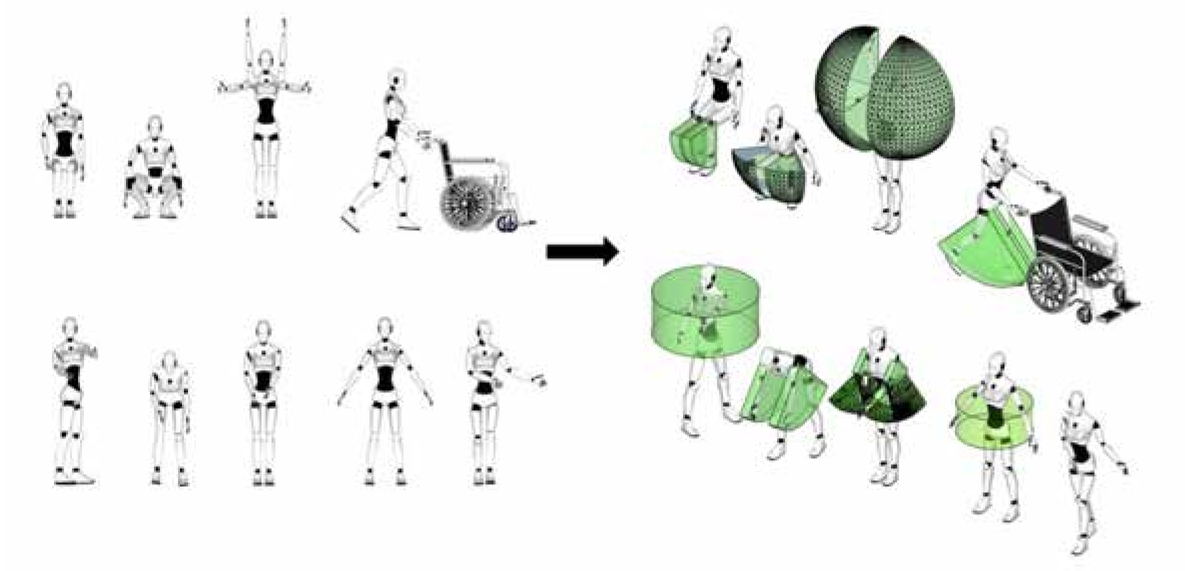


Figure 2 Construction of Dynamic Models of Spatial Requirements for Robots in Different Scenarios of Smart Elderly Care Communities - Taking bipedal humanoid robots as an example

3.2 Accessibility Analysis and Barrier-Free Optimisation Design for Care Robots

From a refined two-dimensional spatial perspective, this study systematically verifies the navigational accessibility of care robots within home environments and evaluates the rationality of charging and storage area layouts. A key innovation lies in the integration of SLAM (Simultaneous Localisation and Mapping) technology into the analytical framework. Based on dynamic models representing the spatial requirements of robots during actual operations, the robot's physical dimensions are defined as the unit scale for grid-based spatial processing. Functional zones within elderly residential spaces are then transformed into planar grid maps accordingly.

This process not only accounts for the geometric configuration of rooms but also carefully distinguishes critical factors such as furniture placement and corridor widths to ensure the accuracy and practical applicability of the model. The grid-mapped spatial layout is further subjected to scientific verification of movement flow lines, with detailed annotations of obstacle locations and the corresponding obstructed areas. This enables the construction of a comprehensive robot navigation map, providing a precise spatial reference for assessing movement feasibility and guiding subsequent optimisation strategies (Figure 3).

Figure 3 Spatial streamline verification of elderly care robots based on the SLAM principle

3.3 Simulation of Spatial Interaction and Environmental Perception for Care Robots

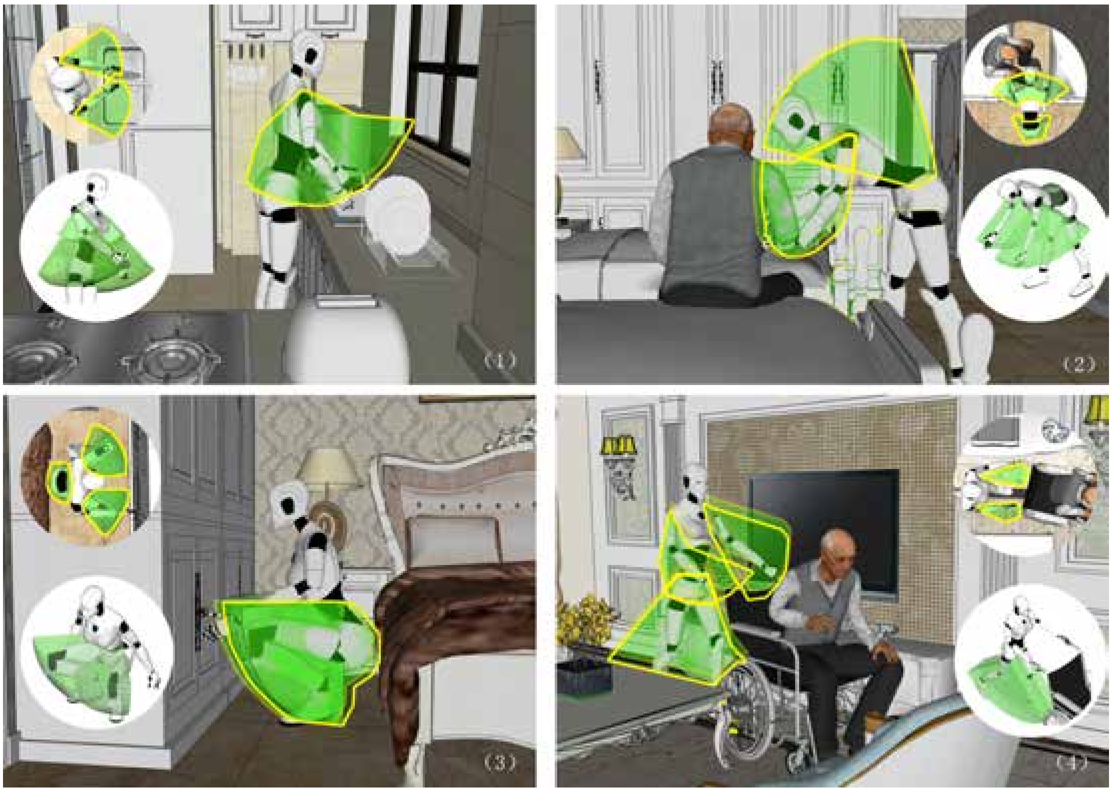
This part of the study focuses on simulating and verifying care robot interactions within eldercare residential spaces. High-precision three-dimensional reconstructions of the living environment are created using architectural modeling software. Through meticulous measurement and accurate modeling, the structural layout of rooms, furniture arrangements, and spatial dimensions are faithfully reproduced to ensure a high level of model fidelity. A dynamic model of the robot, constructed based on its actual dimensions and motion characteristics, is then embedded into the 3D residential space (Figure 4). Using this integrated model, the robot's movement trajectories and posture variations across different scenarios are simulated to assess its spatial adaptability and to identify or predict potential mobility barriers and spatial conflicts.

The Unity platform is employed to simulate the complete process of robot task execution within eldercare environments. Unity provides a realistic representation of interactions between the robot and household furniture. Simulations include daily tasks such as cleaning, transporting objects, and assisting with mobility. Throughout these scenarios, the robot's motion smoothness, operational stability, and physical interactions with furniture are observed and recorded. Based on the simulation outcomes, targeted spatial adjustment strategies are proposed.

Furthermore, the study incorporates the preferences of elderly users and the functional requirements of robotic sensors to evaluate and optimise soft furnishings within the residential space. It examines whether elements such as curtains, carpets, and decorative items interfere with robotic operations—particularly during movement or task execution—and whether they impact sensor performance. Methods from environmental behavior studies are utilised to understand how soft furnishings influence spatial use and robotic functionality, ensuring that such elements do not hinder sensor performance or cause disruptions in path planning. Additionally, the effects of soft furnishings on task efficiency and robot stability are assessed through simulation testing, allowing for the identification of soft furnishing configurations that meet both the preferences of older adults and the operational needs of robotic systems.

To enhance the environmental perception and human–robot interaction capabilities of care robots within residential spaces, this study proposes the deployment of an environmental sensing system to optimise the robot's ability to interpret its surroundings and respond to the needs of elderly users. For example, depth cameras, Li-DAR sensors, and smart detectors can be strategically installed in key areas such as bedside zones and bathrooms to assist robots in accurately recognising spatial structures and dynamic obstacles. This setup improves the efficiency of path planning and task execution. In addition, integrating voice recognition technologies enables multi modal interaction—such as voice commands and gesture recognition—allowing elderly users to communicate with robots more intuitively and conveniently.

Following simulation-based validation and analysis, the study integrates elderly users' physiological and psychological needs, behavioral habits, and the operational requirements of robots to propose an optimised spatial layout and functional configuration. This optimised scheme is designed to meet the dual demands of eldercare and robotic functionality. It includes the generation of annotated maps illustrating the robot's activity ranges and proposes a series of spatial optimisation strategies. These include: public space and circulation design, dedicated charging and storage zones, barrier-free accessibility features, privacy-preserving spatial segments, smart home integration systems, and environmental perception and interaction interfaces. Together, these recommendations provide both theoretical support and practical guidance for the development of intelligent aging-in-place environments within smart eldercare communities.



Washing dishes, (2) Helping an elderly person get up, (3) Doing housework and picking up items, (4) Pushing a wheelchair

Figure 4. Take the bipedal humanoid robot as an example - schematic diagram for verifying the spatial dimensions of the working scene simulation

3.4 Key points of spatial design for nursing robots

-1-Bedroom : Intelligent Spatial Reconfiguration for Dressing and Bed Transfers

As the most frequently occupied and private area for elderly residents, the bedroom must be proactively adapted to accommodate robotic assistance in two critical tasks: dressing and getting in and out of bed. Although dressing appears simple, it involves frequent posture changes (sitting, standing, arm-raising), garment delivery, and fine manipulation. During these operations, the robot must maintain a stable working distance from the bed and frequently transition among the bed, wardrobe, and dressing chair. Therefore, the spatial layout around the bed should allow 360-degree accessibility, and storage elements such as drawers and hanging rails must be adjusted to robot-reachable heights, potentially integrated with smart lift systems. This multi-point coordination not only improves task efficiency but also lays the spatial foundation for transforming the bedroom into a wearable-assistance unit in future designs (Figure 5).

Bed transfers, on the other hand, rely more heavily on the robot's ability to support body weight and stabilize the user's posture. The conventional layout—where beds are placed against walls on both sides—prevents parallel robotic access and must be reconsidered. A lateral clearance of at least 80 cm should be maintained along at least one side of the bed. Additionally, the bed frame itself should comply with robot-compatible structural standards, including appropriate height, unobstructed bed edges, and built-in sensor interfaces. Such a forward-looking design approach transforms the bedroom from a purely human-centered spatial model into a human–robot collaborative environment, enabling a new paradigm for intelligent caregiving at home.

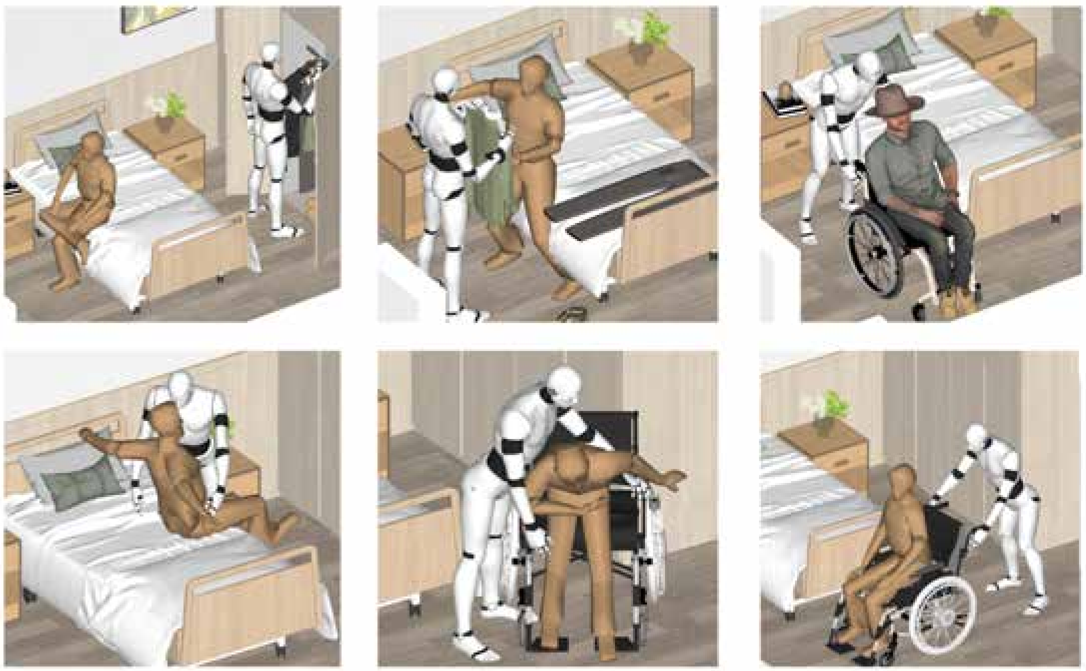


Figure 5. A schematic diagram of a care robot assisting the elderly in the bedroom space

-2-Living Room : Adaptive Upgrades in Public Zones Triggered by Feeding and Wheelchair-Assistance Behaviors

In the living room, where robots assist with tasks such as feeding and wheelchair propulsion, the space functions not only as a site for leisure and social interaction, but also as a dynamic caregiving operations platform. Feeding tasks require the robot to maintain a stable front-facing position relative to the elderly person, perform lifting actions, and deliver food with precision. This necessitates a layout that ensures accessibility and interaction compatibility—particularly in terms of adequate clearance between furniture, movable chairs, and slip-resistant flooring with guided navigation features. Future intelligent living rooms should adopt behavior-driven layouts, enabling real-time responsiveness to action chains such as "feeding – turning – obstacle avoidance – repositioning," while reserving zones for information interfaces and power docking points to support seamless human-robot-environment integration (Figure 6).

Wheelchair-pushing tasks demand precise spatial adaptations in terms of continuous circulation paths, doorway widths, and turning radii. The robot must detect and navigate through spaces at a height below 1 meter, avoid obstacles, and stably maneuver a weighted object, all while monitoring the elderly user's posture in real time. Common mixed-function household furniture layouts may hinder such mobility, introducing unpredictable obstructions. Therefore, design measures such as pathfinding cues, clearance control, and furniture-aided turning zones are necessary to optimize routes. The future senior-friendly living room will incorporate service flow logic, planning both primary and fallback robotic circulation paths, and will evolve into a truly intelligent and inclusive residential environment—where pets, home appliances, humans, and robots coexist in harmony.

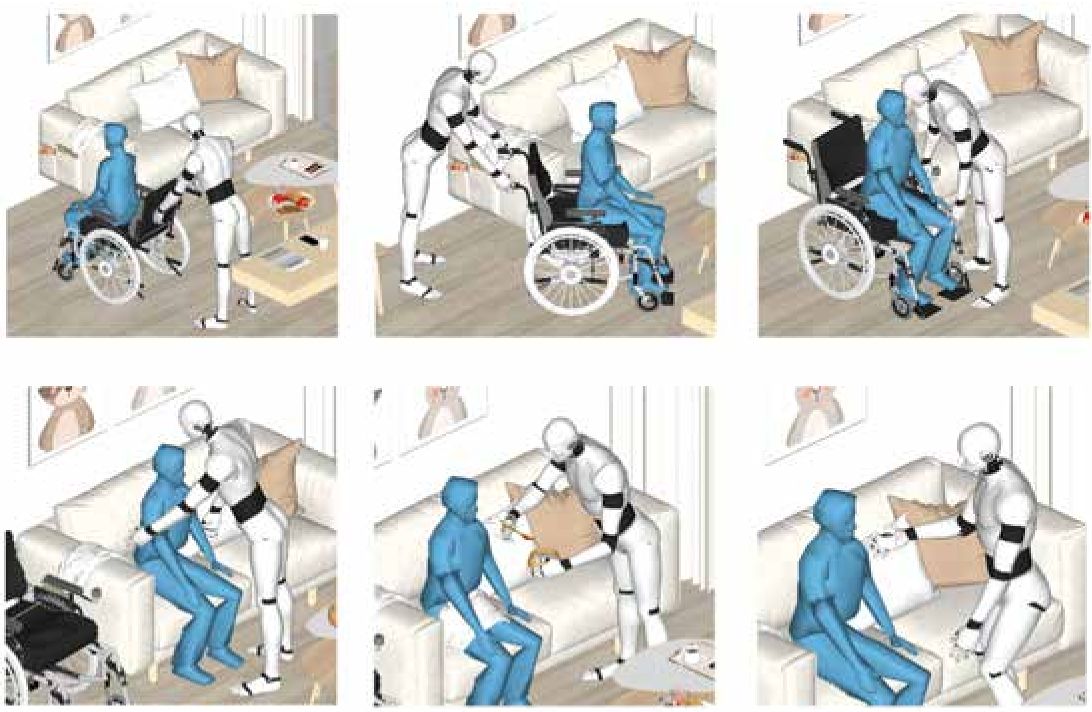


Figure 6. A schematic diagram of a care robot assisting the elderly in the living room space

-3-Bathroom : Fine-Tuned Spatial Responses for Bathing and Toileting Assistance

As the functional capabilities of caregiving robots continue to advance, assisting elderly users with toileting and bathing within the bathroom has become a crucial component of intelligent eldercare systems. Compared to traditional human-assisted care, robotic operation demands a higher degree of spatial precision and accessibility. For example, during bathing, the robot must perform a sequence of actions—supporting, washing, and transferring—typically from a lateral or rear position relative to the user. This necessitates not only sufficient rotational and extension space for dynamic movements, but also the integration of wet-zone electrical safety separation, non-slip waterproof materials, and proper drainage slope. Thus, bathrooms can no longer be designed solely based on minimal usable area standards; they must be redefined through a three-dimensional coordination model that aligns robotic motion, operating space, and embedded safety infrastructure (Figure 7).

Toileting tasks, on the other hand, require the robot to assist with sit-to-stand transfers, provide posture stabilization, and manage clothing adjustments—all within constrained spatial envelopes. This introduces new layout standards for the bathroom, including minimum clearances in the toilet zone, unobstructed side access around the toilet, and handrail configurations that accommodate the robot's arm reach and movement trajectories. Future intelligent bathroom design must go beyond conventional aging-in-place principles and evolve toward dual compatibility with humans and robots. By anticipating robotic workflow and movement patterns, such designs can embed both physical and digital interfaces, laying the groundwork for fully automated care environments in residential and institutional eldercare settings.

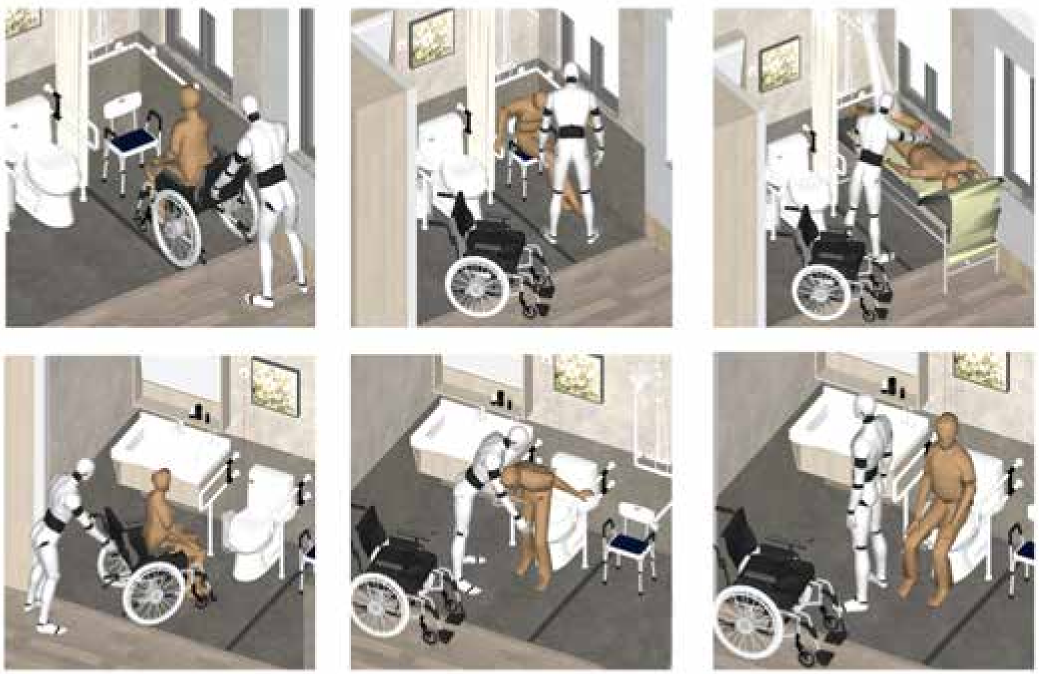


Figure 7. A schematic diagram of a care robot assisting the elderly in the bathroom space

4 Conclusion

As elderly care services continue to evolve toward greater intelligence and diversification, the integration of robots represents not only a technological innovation but also a fundamental shift in the organization and spatial logic of architectural environments. The spatial demand modeling method for care robots proposed in this study serves as a bridge between intelligent devices and architectural design, offering high scalability and practical applicability. By analyzing the motion characteristics of care robots in various caregiving tasks and applying principles of robotic kinematics, this research constructs an environmental requirement model to quantify the spatial needs associated with different tasks. It further assesses the mobility and accessibility of robots within typical eldercare spaces such as bedrooms and living rooms, and proposes environmental layout optimizations to enhance compatibility with robotic movement and operational zones. Additionally, the study explores the interactive relationship between robots and furniture, soft furnishings, and barrier-free facilities, and incorporates smart perception systems to improve robotic adaptability to complex residential environments.

Starting from six core caregiving tasks in real-world eldercare scenarios, this study provides an in-depth analysis of spatial adaptation principles and design requirements for robotic assistance in three representative spaces: bathroom, bedroom, and living room. A three-dimensional translational framework of "task–motion–spatial demand" is proposed to uncover spatial compatibility bottlenecks inherent in traditional human-centered residential layouts when confronted with robotic operation. Looking forward, this framework may be further enhanced by integrating machine learning, behavioral simulation, and multi-scenario dynamic optimization techniques, leading to the development of multi-scale design models that support human–robot–space co-evolution in intelligent eldercare communities offering both theoretical grounding and practical pathways for healthy aging in the urban context.

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