Beyond Vacuuming: How Can We Exploit Domestic Robots' Idle Time?

Yoshiaki Shiokawa
Department of Computer Science
University of Bath
Bath, United Kingdom
ys2445@bath.ac.uk

Winnie Chen
Department of Computer Science
University of Bath
Bath, United Kingdom
yc2488@bath.ac.uk

Aditya Shekhar Nittala
Department of Computer Science
University of Calgary
Calgary, Canada
anittala@ucalgary.ca

Jason Alexander
Department of Computer Science
University of Bath
Bath, United Kingdom
jma73@bath.ac.uk

Adwait Sharma
Department of Computer Science
University of Bath
Bath, United Kingdom
as5339@bath.ac.uk

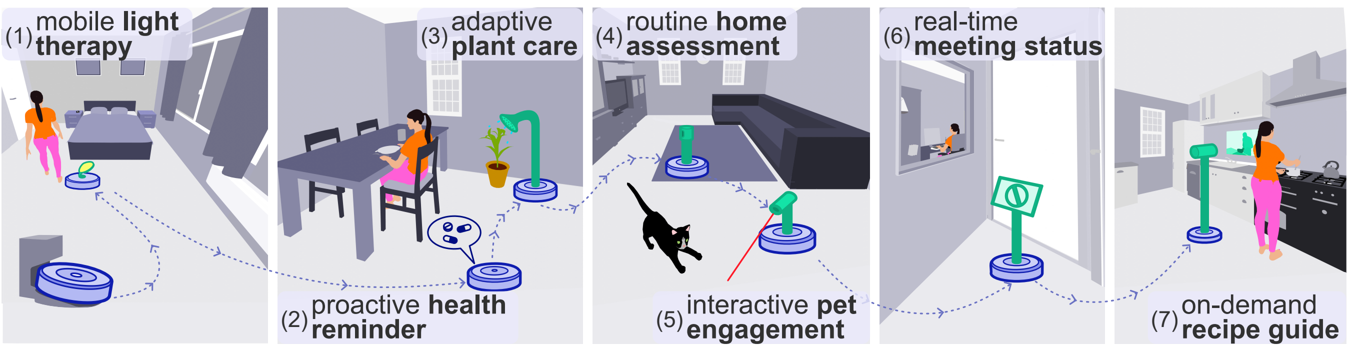


Figure 1: We explore how domestic robots can be repurposed to enhance modern lifestyles through novel applications and interactions. Using a vacuum robot as an example, we identified 12 key design dimensions and over 100 use cases. Here, we showcase a reappropriated domestic robot supporting user Taylor throughout a typical day (left to right): it (1) functions as a mobile light therapy device to start the morning; (2) provides pill reminders before she begins breakfast; (3) delivers plant care while Taylor eats; (4) performs home assessments to log a daily house check; (5) facilitates interactive pet engagement while Taylor is away; (6) displays a "Do Not Disturb" sign outside the room during calls; (7) projects cooking recipes onto the kitchen counter as she prepares dinner. We also demonstrate the feasibility of this design space with four proof-of-concept prototypes.

Abstract

We are increasingly adopting domestic robots (e.g., Roomba) that provide relief from mundane household tasks. However, these robots usually only spend little time executing their specific task and remain idle for long periods. They typically possess advanced mobility and sensing capabilities, and therefore have significant potential applications beyond their designed use. Our work explores this untapped potential of domestic robots in ubiquitous computing, focusing on how they can improve and support modern lifestyles. We conducted two studies: an online survey (n=50) to understand current usage patterns of these robots within homes and an exploratory study (n=12) with HCI and HRI experts. Our thematic analysis revealed 12 key dimensions for developing interactions with domestic robots and outlined over 100 use cases, illustrating how these robots can offer proactive assistance and provide privacy. Finally, we implemented a proof-of-concept prototype to demonstrate the feasibility of reappropriating domestic robots for diverse ubiquitous computing applications.

CHI '25, Yokohama, Japan

ACM ISBN 979-8-4007-1394-1/25/04
https://doi.org/10.1145/3706598.3714266

CCS Concepts

• **Human-centered computing** → **Ubiquitous and mobile computing**; **Interaction devices**.

Keywords

domestic robots, ubiquitous, interaction, design space

ACM Reference Format:
Yoshiaki Shiokawa, Winnie Chen, Aditya Shekhar Nittala, Jason Alexander, and Adwait Sharma. 2025. Beyond Vacuuming: How Can We Exploit Domestic Robots' Idle Time?. In *CHI Conference on Human Factors in Computing Systems (CHI '25), April 26–May 01, 2025, Yokohama, Japan.* ACM, New York, NY, USA, 17 pages. https://doi.org/10.1145/3706598.3714266

1 Introduction

Robots are becoming an integral part of our daily lives, with domestic robots such as vacuum cleaners and lawnmowers growing in popularity and expected to see annual market growth of 18.8% by 2028[1]. As these technologies become more prevalent, it is crucial to explore how to optimise them to assist users better. A large body of prior research in Human-Computer Interaction (HCI) and Human-Robot Interaction (HRI) has focused on key areas such as adoption trends [1, 29, 78, 79], physical personalisation [92, 93], social and long-term usage impact [45, 107], and technological improvements [2, 82, 91]. However, while these robots usually only spend a small fraction of time executing their specific task, they remain idle for significant periods. This untapped idle time presents an opportunity to repurpose robots for additional tasks or interactions, thereby enhancing their overall utility and supporting people's lives. This idea also aligns with the growing need for adaptable robots and integrated systems that can seamlessly fit into our daily lives, as highlighted by [19, 32].

Despite technological advancements and their increasing presence in our living spaces, domestic robots are often perceived as limited, single-purpose devices [108]. Recent research has focused on extending the capabilities of domestic robots beyond single-task applications. For example, toolkits such as Dobb-e [81] and Stretch 3[2], as well as commercial products like Amazon Astro[3] and Samsung Ballie[4], illustrate the shift toward multi-purpose robots. In the same vein, existing research has explored the use of robots for multiple domestic tasks, such as home organisation [69], task allocation with a fixed robotic arm [42], identifying 25 existing household chores that robots might perform [21], and user expectations from humanoid robots performing traditional household tasks [20]. Although prior studies have provided valuable insights, they often focus on stationary or humanoid robots performing predefined household tasks. In contrast, we investigate how mobile domestic robots, such as robot vacuums, can be repurposed to support a broader range of activities across different areas of the home. By leveraging their mobility, we aim to extend their functionality beyond conventional chores, opening up new possibilities for domestic robots in the home.

This paper shifts focus to an overlooked yet essential aspect: the idle time of domestic robots. Idle time, defined as periods when a robot is not performing its primary task, presents unique opportunities for value-adding interactions. For instance, a robot vacuum could use its idle time for tasks like home security monitoring or watering plants, leveraging its advanced sensors, such as LiDAR and infrared cameras, as well as its mobility (Figure 1). This type of versatility is unique compared to most stationary smart home devices (e.g., smart speakers, thermostats, or security cameras), which lack mobility. Domestic robots with mobility (e.g., robot vacuums) can extend their utility beyond their primary tasks by physically navigating spaces to perform diverse functions. This capability opens up new possibilities for the HCI community to enhance household efficiency and convenience.

Prior research on utilising idle periods of smart home devices has focused primarily on technical improvements. For example, stationary devices like voice assistants use idle time for tasks such as model updates [103] or information processing [23]. Similarly, research on robots has explored idle motion for social purposes, such as signalling activity or enhancing social presence [7, 8, 10, 58], or improving social appropriateness [68]. Studies also suggest that active devices create a more positive user mindset compared to idle ones [95]. However, the idle time of domestic robots remains underutilised for practical tasks. To the best of our knowledge, this paper is the first to highlight the untapped potential of domestic robot's mobility and systematically explore how to repurpose idle time for diverse, value-adding interactions such as home maintenance, on-demand assistance, and pet care.

We propose that modern domestic robots should not be seen solely as cleaning machines but as versatile tools equipped with sensors and mobility in three-dimensional space. Our approach differs from previous work, which repurposed domestic robots for specific tasks like providing haptics in virtual reality [106]. Instead, we create a comprehensive design space to expand the interaction capabilities of these robots. While methods exploring idle time in devices like smart speakers are valuable, they are only partially applicable to domestic robots due to the limited functionality of such devices compared to the advanced capabilities of modern robots. We aim to leverage robot's idle time and mobility to unlock new applications in ubiquitous computing.

To guide our investigation, we have formulated the following research questions:

- **RQ1:** What are the current usage patterns of domestic cleaning robots from the end-user's perspective?
- **RQ2:** What is the design space for creating interactions with domestic robots?
- **RQ3:** What additional functions can domestic cleaning robots perform during idle periods?

To address **RQ1**, we conducted an online survey with 50 participants, which revealed that robot vacuum cleaners often experience idle periods (e.g., an average cleaning duration of 1 hour and 47 minutes), offering an introductory context for exploring additional functionalities during these periods.

For **RQ2** and **RQ3**, we conducted an exploratory study involving interviews with 12 HCI and HRI experts to identify possible capabilities. Through thematic analysis, we developed a design space comprising 12 dimensions for enhancing interactions with domestic robots. The interviews also revealed over 100 potential applications to expand robot functionalities beyond their primary tasks. Finally, we demonstrate the technical feasibility of our design space by implementing four working applications using a domestic robot. Collectively, our approach underscores how domestic robots can be leveraged to improve and support modern lifestyles.

[1] https://www.marketsandmarkets.com/Market-Reports/household-robot-market-253781130.html
[2] https://hello-robot.com/stretch-3-product
[3] https://www.amazon.com/Introducing-Amazon-Astro/dp/B078NSDFSB
[4] https://news.samsung.com/us/samsung-ballie-ai-companion-robot-home-video-ces-2024/

To summarise, the main contributions of this research include:

- Findings from an expert study, presented as a 12-dimensional design space for creating interactions with domestic robots.
- A compilation of over 100 application cases to expand robot functionalities. This list serves as a rich resource for understanding the wide range of tasks that domestic robots can perform beyond their defined role, from household chores to entertainment and companionship.
- Evidence of the practical feasibility of our design space, demonstrated through the implementation of four proof-of-concept applications.

2 Related work

We conducted a literature review across both HCI and HRI fields to examine how domestic robots are used. Prior research mainly focuses on robots' primary tasks and their impact on households, which informs our exploration of how cleaning robots can be utilised during idle periods.

2.1 Design Challenges and Opportunities in Domestic Robot Interaction

Research on domestic robots has largely focused on their social integration and user adoption. Early works by Forlizzi [33, 34] demonstrated how robots like Roomba reshaped household routines and integrated socially and aesthetically. Young et al. [107] identified key social factors influencing the adoption of domestic robots. While these studies provide valuable insights, they primarily address social and integration issues, leaving the role of robots as interactive conduits in home environments underexplored. A significant body of design guidelines centres on specific use cases. For example, Moharana et al. [69] explore robots in organisation and storage tasks. Other studies focus on fostering child development through reading [57], enabling mobile robotic telepresence [16], and offering personalised rehabilitation support [17].

It is important to note that household dynamics create unique design challenges and opportunities beyond individual use cases. These dynamics—including diverse user needs, routines, and environmental factors—require careful consideration when designing interactive systems, especially those integrated into home environments. Most closely related to our work is Herr et al. [42], which explores user expectations, task allocation, and interaction methods for fixed robotic arms. In contrast, our research incorporates the mobility of robots, which introduces distinct challenges and opens up new opportunities for advancing domestic robots.

To provide designers and engineers with a comprehensive design space for novel domestic robot applications, we use the Research-through-Design (RtD) methodology [112]. In robotics, RtD has been applied to co-design social robots with older adults [67], tabletop telepresence [28], extra-linguistic cues [49], and wearable companions [24]. Others have focused on, artificial movement sounds [74], spatially distributed robot sound influences [73], playful interventions for elderly care [5], and socially assistive robots to reduce anxiety [56]. These studies underscore the usefulness of RtD in creating new interactions and functionalities. However, existing work does not explore idle time, which are periods when robots are not engaged in their primary functions, as a design opportunity. Our work is the first to apply RtD to reappropriate idle time in domestic robots, framing it as an interaction resource. This approach expands the functional capabilities of domestic robots and opens up new research opportunities at the intersection of robotics and ubiquitous computing.

2.2 Multi-Functional Domestic Robots: Consumer Products and Research Works

Domestic robotics has advanced significantly in recent years due to a growing need for versatile help around the house. In this context, Fong et al. [32] systematic review underscores the importance of adaptability in robots, similarly Brush et al. [19] highlight the challenges posed by managing separate home device subsystems, advocating for more integrated and flexible solutions. This section highlights key developments in both commercial products and research prototypes. It shows that more focus is being placed on creating multi-functional and adaptable designs to meet user needs and expectations.

Commercial products like Amazon Astro[5], Samsung Ballie[6], Pepper[7], Unitree G1[8], and 1X[9] have teased a range of promising applications, highlighting the market's growing interest in multi-functional robots. Research examples include Dobb·E, which is a versatile general-purpose mobile robot capable of learning manipulation actions, such as picking up tissue paper and opening a microwave door, from five minutes of user demonstration [81], ROBEAR is a nursing robot capable of heavy-lifting tasks and social interactions [46], and Hobbit is a care robot featuring user entertainment as well as fall detection and prevention [31]. Recent work integrating LLMs has pushed the boundaries of robotic learning [109]. Some exemplary works include using LLM to generalise a set of rules to organise items on a floor according to a user's preferences [102] and generating action plans for general-purpose robots [2, 82]. For a more in-depth exploration of the current trends in HRI, we refer readers to these systematic surveys [37, 52].

While prior research has demonstrated the usefulness of domestic robots in performing varied tasks, it often lacks a comprehensive approach to exploring their full potential. Our work addresses this gap by introducing a structured design space derived from expert interviews and thematic analysis. This design space can aid designers and researchers in creating new use cases and expanding the potential of domestic robotics. A key contribution of our work is the reappropriation of existing products, such as the Roomba, transforming them into multi-functional robots capable of performing diverse tasks in varied home environments.

2.3 Use of Idle Period in Smart Home Devices

A large body of work has leveraged idle times to drive technical improvements in smart-home devices, such as smart speakers and IoT devices. Pawlaszczyk et al. [23] analysed the Echo 3 and described that it was permanently in standby mode to record small

[5]https://www.amazon.com/Introducing-Amazon-Astro/dp/B078NSDFSB
[6]https://news.samsung.com/us/samsung-ballie-ai-companion-robot-home-video-ces-2024/
[7]https://www.softbank.jp/en/robot/
[8]https://www.unitree.com/g1
[9]https://www.1x.tech/neo

Time of day (hour)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Usage Distribution (%)	0.0	0.0	0.0	0.0	0.0	0.0	3.5	3.5	10.5	15.8	21.1	1.8	3.5	3.5	0.0	7.0	7.0	5.3	10.5	1.8	3.5	0.0	1.8	0.0

Figure 2: Distribution of robot vacuum cleaner usage patterns throughout the day among 50 survey participants.

sections of the ambient noises and initiated the voice control system once it identified keywords. Xu et al. [103] introduced CHA, an edge-based caching framework for voice assistant systems. It saved the feedback locally during the active period and adopted batch adaptive learning on the feedback when it was in an idle state derived from long-term tracking of the usage pattern. In terms of robots, this has predominantly focused on features like blinking, posture shifts, and non-verbal cues [8, 62]. Other works showed that idle behaviours, such as head movements and hand gestures, can improve perceptions of human-likeness and social appropriateness [7, 10, 58, 68]. Work by Söderlund shows a busy service robot received a higher positive overall evaluation from participants than an idle one [95]. Debie et al. [26] conducted a literature survey on the progress of swarm robotics, focusing on how multiple robots use distributed control and collective behaviours to collaborate and achieve shared objectives in complex environments. Most pertinently, Sung et al. [93] investigated Roomba ownership and usage patterns, providing insights into how users integrate domestic robots into their daily lives. However, their study did not include information on these devices' usage patterns or idle periods. In summary, this body of literature illustrates two key findings: (i) there is a higher user preference for domestic robots to be busy, resulting in positive perception [95]. (ii) while some studies have explored idle behaviours, to the best of our knowledge, there is no foundational work that synthesises and develops a multi-dimensional design space to leverage the opportunities presented by idle domestic robots. In our work, we contribute an end-user survey to quantify when and how long domestic robots remain idle throughout the day, along with a comprehensive design space to inform future developments in this area.

3 Preliminary Survey: Usage Time

While robot manufacturers provide standard cleaning and charging times for vacuum cleaners[10,11], these metrics do not capture the real-world idle time influenced by user-centric factors such as home size, behaviour, and pet ownership. Sung et al. [93] examined Roomba owner demographics and usage trends, but the timing or duration of robot activity was not detailed. To fill this gap, we conducted an online survey of 50 robot vacuum owners (30 male, 18 female, 2 non-binary; average age 35.66, SD=6.63) from North America (48%), Europe (34%), and Asia (18%). Most respondents worked from home (46% exclusively, 40% hybrid).

Our survey revealed that 40% of users deploy their robots daily, with an average cleaning cycle of 1 hour and 47 minutes and a charging duration of 4 hours and 13 minutes. Notably, 46% run their robots between 7 AM and 11 AM, with significant idle periods throughout the day (as shown in Figure 2). These idle periods, combined with accessible storage locations (often the living room), suggest the potential for leveraging these robots for secondary functions without requiring active user input. This resonates with prior work by Sung et al. [93], who found users typically operate robots when away or engaged in other tasks.

In sum, the survey revealed idle time and insightful usage patterns in domestic robots, motivating an exploratory study in the next section with HCI and HRI experts to define an interaction design space and identify potential applications.

4 Exploratory Study with HCI & HRI Experts

To explore the potential capabilities of domestic robots and define a design space for interaction, we conducted an exploratory study with experts from industry and academia. This section presents the findings from our thematic analysis, which identified 12 key dimensions and over 100 use cases to guide future designs and interactions with domestic robots.

4.1 Participants

We recruited a diverse group of 12 participants (5 female, 7 male) for our study, all specialising in either Human-Robot Interaction (HRI) or Human-Computer Interaction (HCI). Their experience ranged from 1.5 to 23 years (M=7.79, SD=6.4), including PhD students, academic faculty, and industry professionals.

In addition to professional diversity, participants represented a diverse range of cultures from six different countries. During our interviews, they also shared insights into their lifestyles, including pet ownership and living arrangements. All participants were fluent in English. Their demographic details are summarised in Table 1.

4.2 Procedure

We conducted semi-structured teleconference interviews via Microsoft Teams, with sessions recorded for subsequent transcription. The interview process was divided into three phases: (i) Preparation—participants were briefed about the study, provided with an information sheet and consent form, and responded to initial demographic questions; (ii) Ideation—participants discussed their daily routines and viewed videos of three domestic robots (Amazon Astro, Samsung Ballie, and Hello-Robot Stretch 3) to stimulate creative thinking about potential applications, employing methods from prior research [6, 60, 97]; (iii) Designing—participants co-created scenarios describing how domestic robots could support their everyday tasks and ranked these scenarios according to their perceived usefulness. At least two authors were present during each interview to ensure data consistency and reliability. Each interview lasted approximately one hour.

4.3 Thematic Analysis

We analysed the interview transcripts using thematic analysis [18], utilising both inductive and deductive coding strategies [15]. The analysis began with line-by-line inductive coding to address our second research question (RQ2): 'What is the design space for creating interactions with domestic robots?' This initial phase identified

[10]https://homesupport.irobot.com/s/article/10225
[11]https://homesupport.irobot.com/s/article/26647

ID	Gender	Residence	Occupation	Experience (in years)	Area of Expertise
1	M	UK	PhD Candidate, Industry (Business Development)	1.5	HRI (Multi-robot Systems)
2	F	S.Korea	Assistant Professor in Computer Science	2.5	HCI (Haptic Interfaces/Interaction)
3	F	Germany	PhD Candidate	3	HRI (Robot Intent: Exoskeletons and Limbs)
4	M	Singapore	Industry (Research Engineer)	3	HCI (VR Data Visualisation, Human-AI Interaction, Design Fiction)
5	F	UK	PhD Candidate	5	Computer Vision and HCI
6	F	UK	Postdoctoral Researcher	5	HCI (Design and Older Adult Care)
7	M	USA	PhD Candidate	6	HRI/HCI
8	M	S.Korea	PhD Candidate	6	HCI (Input Techniques, Sensing Techniques, Eye-gaze Interaction and Haptics)
9	M	Singapore	Assistant Professor in Computer Science	10	HCI (Multimodal Interactions/Virtual Agents, Robots that Teach Humans)
10	F	UK	Assistant Professor in Computer Science	10	HRI (Long Term, In-home Robots)
11	M	UK	Assistant Professor in Mechanical Engineering	18.5	Assistive Technology for Visually Impaired or Deaf, Haptics
12	M	Canada	PhD Candidate, Programmer	23	HRI

Table 1: Professional and demographic details of study experts.

233 discrete scenarios. Subsequently, we refined our approach to address our third research question (RQ3): 'What additional functions can domestic cleaning robots perform during idle periods?'. We combined inductive codes with concepts from prior literature (deductive approach) and developed a structured codebook. This codebook was then iteratively refined by other co-authors and guided the development of our design space.

5 Design Space

Drawing on insights from expert interviews and informed by existing literature, we identified 12 key dimensions relevant to the design and development of interactions with domestic robots:

D1 **Interaction Entity** (Figure 3): Domestic robots are uniquely capable of interacting with a diverse range of entities—other robots [61], devices (both local [11] and networked [53, 55]), the environment [94], and users (both people [35] and pets [40, 72])—due to their inherent mobility. This mobility eliminates spatial constraints, enabling robots to perform infeasible tasks for stationary devices like voice assistants in smart speakers, which are limited to nearby or network-connected entities. For instance, during idle time, a mobile robot can autonomously navigate multiple rooms to collect bin bags or engage with pets by moving to their location.

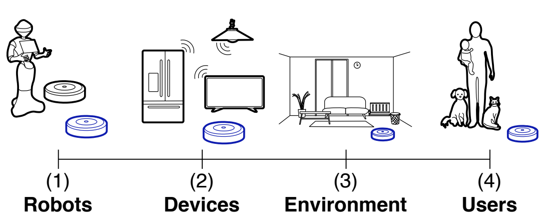


Figure 3: *Interaction Entity.* E.g., (1) Multiple robots collaborate to search for a lost item; (2) A robot manages smart devices, such as changing a TV channel; (3) A robot organises household items; (4) A robot assists the user in taking a family photo.

D2 **Interaction Scale** (Figure 4): This dimension describes the ratio of robots to users in an interaction—one-to-one, one-to-many, many-to-one, many-to-many)—similar to the "human-robot-ratio" concept introduced by Yanco et al. [104]. While some flexibility in interaction scale might exist with other devices, the speed and seamlessness of these transitions distinguish mobile robots. Unlike stationary devices, mobile robots can dynamically and rapidly shift their interaction scale due to mobility. For example, a single robot could patrol an entire house, interacting with multiple users in different locations (one-to-many), while a voice assistant requires separate installations in each area. Similarly, multiple robots could collaborate with a team of users on a distributed task (many-to-many), with transitions happening far more quickly than stationary device alternatives.

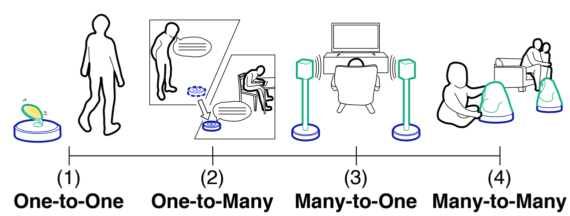


Figure 4: *Interaction Scale.* E.g., (1) A single robot with a SAD lamp provides mobile light therapy to a user; (2) A single robot relays a message across multiple users; (3) Multiple robots create an immersive sound experience for a single user; (4) Multiple robots facilitate social interactions within a group, such as a family gathering.

D3 **Augmentation Approaches** (Figure 5): Mobile robots can extend their capabilities through various augmentation approaches, such as attachable carts, helmet-style bases [61], and docking with robot arms. These augmentations complement advanced sensing technologies and are particularly effective due to the robot's mobility [98, 105]. For example, while a stationary device can suggest recipes, a mobile robot with a cart can physically transport groceries. This embodied action—manipulating and transporting objects within the environment—is a direct result of the robot's mobility, distinguishing it from stationary devices.

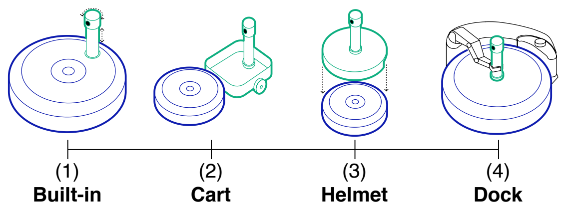


Figure 5: *Augmentation Approaches.* E.g., (1) A built-in periscope camera provides elevated viewpoints; (2) An attachable cart facilitates item transport; (3) Swappable helmet bases enable function changes; (4) Robotic arms attached to a charging station enable automatic component reconfiguration of a robot.

D4 **Human-Robot Relationship** (Figure 6): This dimension outlines the relationship between humans and robots within interactions, defining their respective expectations and responsibilities [66, 80]. Key roles include: Supervisor (directs activities), Operator (controls via interface), Bystander (passively observes), Cooperator (performs complementary tasks), Collaborator (works in teams), Service Agent (provides services), and Companion (acts as a pet or friend). For a detailed discussion of these roles, please refer to [66] and [80] as it is beyond the scope of our project. While stationary smart devices can fulfil some of these roles, a robot's mobility unlocks richer interactions. For example, a human and a mobile robot can efficiently collaborate in a kitchen, passing items between fridge and cupboards and dynamically swapping positions and tasks.

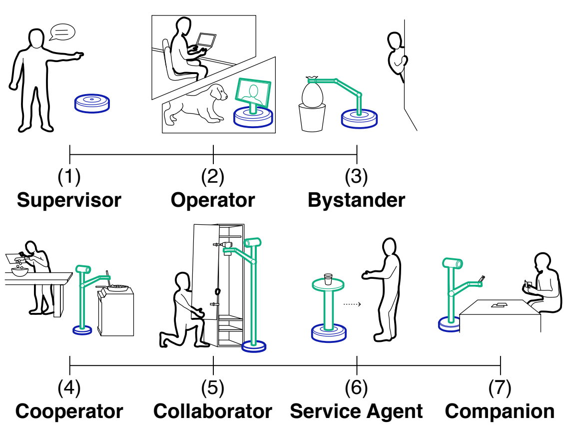


Figure 6: *Human-Robot Relationship.* E.g., A user (1) instructs a robot to check if a door is locked; (2) remotely controls a robot to interact with a pet; (3) observes a robot while it collects bin bags; (4) cooks alongside a robot by working on parallel tasks; (5) collaborates with a robot to assemble furniture; (6) receives a cup of water from a robot; (7) plays cards with a robot.

D5 **Intent** (Figure 7): Robot interactions fulfil various purposes: task-oriented (e.g., laundry [14]), social (e.g., companionship [4, 63]), educational [41], and care-oriented (e.g., accessibility support [46, 83, 86]). A robot's mobility allows it to accomplish these tasks more efficiently than fixed devices, such as cleaning all the windows in a house instead of just the nearest one, as well as providing continuous walking assistance to a user.

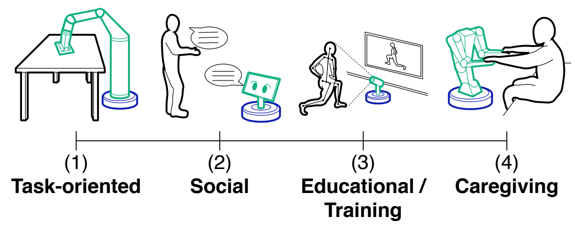


Figure 7: *Intent.* E.g., A robot (1) wipes a tabletop as part of a cleaning task; (2) engages in social conversation using language models; (3) provides feedback to the user during a workout; (4) helps when a user stands and walks.

D6 **Action Types** (Figure 8): Robot actions can be physical (e.g., object interaction [30]), digital (e.g., data processing [84, 88]), or hybrid [38]. While stationary devices are primarily limited to digital actions, mobility enables robots to perform physical actions which are capabilities beyond the scope of stationary devices, such as lifting and moving heavy objects like a sofa with a user.

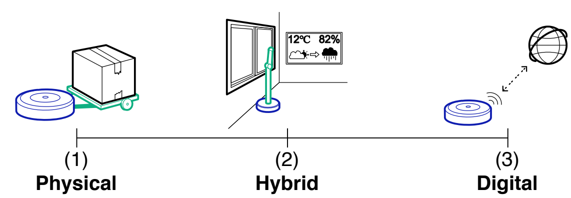


Figure 8: *Action Types.* E.g., A robot (1) carries groceries from the driveway to the house; (2) monitors weather forecasts and closes windows if rain is expected; (3) scans the fridge and suggests items to purchase.

D7 **Spatial Scope** (Figure 9): Robots operate in various locational contexts: specific objects, individual users, particular areas, multiple areas, the entire home, and virtual environments. A stationary device, such as an automatic plant watering system[12], can address single-object or area needs. However, covering multiple objects or areas often requires multiple such devices. In contrast, a single mobile robot can seamlessly address these broader spatial needs, such as patrolling the entire home for security. This ability to dynamically navigate and interact across multiple locations is a key advantage of mobile robots.

[12] https://www.leafypod.one/

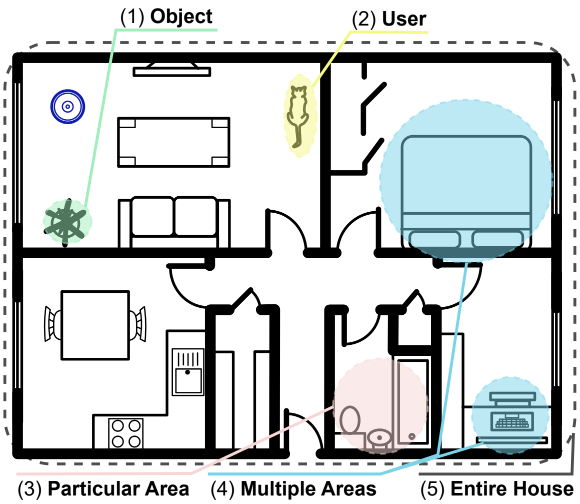


Figure 9: *Spatial Scope.* E.g., A robot (1) waters the bamboo plant; (2) plays with the cat using a laser pointer; (3) dries the bathroom floor; (4) pairs up with another robot to facilitate in-house communication; (5) performs nightly security patrols throughout the house.

D8 **User Proximity** (Figure 10): Operations by robots are conditioned by their various proximities to users: close, nearby, remote, or distant. This influences interaction effectiveness, user experience [101], and user trust [79]. Wearable devices consistently remain "close" (albeit sometimes inconvenient), and stationary devices are limited to "nearby" or "distant" interactions due to their fixed locations. In contrast, mobile robots offer dynamic proximity; e.g., a robot can accompany a user or proactively find them to deliver timely notifications.

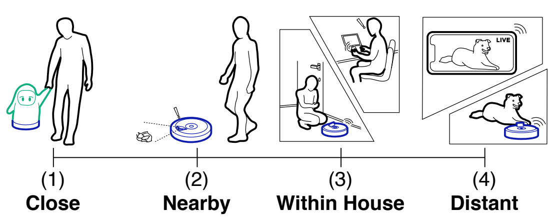


Figure 10: *User Proximity.* E.g., A robot (1) provides contact feedback by rubbing a user with comfortable materials; (2) clears nearby paths and alerts for hazards; (3) opens the door and welcomes a guest while the user is busy; (4) allows users to monitor their pet's condition remotely while at work.

D9 **Interaction Modalities** (Figure 11): Robots interact through various modalities, both in terms of input and output. From the human-to-robot perspective, input modalities include tactile touch [39], visual cues such as gestures [76] and gaze [100], and auditory signals like voice commands [54, 59].

From the robot-to-human perspective, output modalities include tactile feedback such as touch [44], motion [77], visual cues like lights [87], auditory signals such as speech [85, 110], and occasional olfactory feedback [22]. For robot-environment interactions, inputs allow the robot to detect environmental conditions, such as temperature and light [64], while outputs enable the robot to adjust these conditions. Noteworthy, mobile robots can adapt their position to optimise these interactions. For example, a robot can move in front of a user to display a visual warning, unlike stationary devices which are limited by their fixed location.

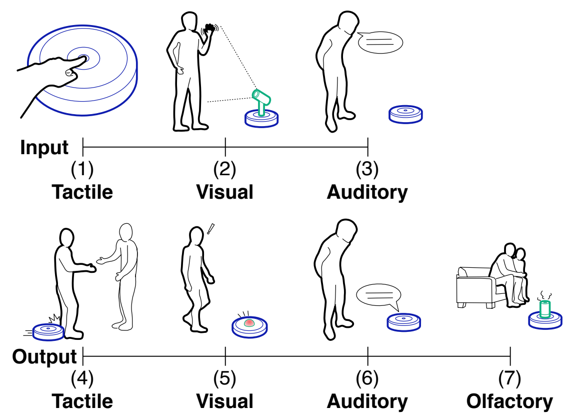


Figure 11: *Interaction Modalities.* E.g., A robot (1) stops when the user presses a button; (2) recognises the user's sign language commands; (3) transcribes the user's spoken words; (4) gently nudges the user as a reminder; (5) provides visual cues, like flashing lights, for notifications; (6) projects sound to alert users (weather warnings); (7) diffuses pleasant scents.

D10 **Task Trigger** (Figure 12): Tasks can be activated through user-initiated commands [71], time-based schedules [12], or event-triggered responses to environmental cues [75]. While these triggers apply to both mobile and static devices, mobility is particularly useful for event-triggered tasks, as it allows robots to respond to events across different locations. For example, a mobile robot can detect unusual sounds in another room and move to investigate the source, a capability static devices lack.

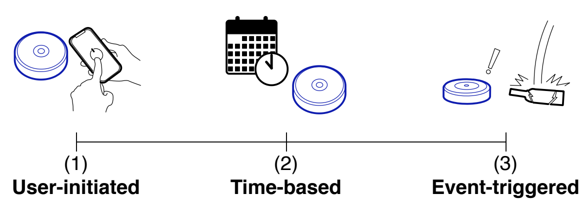


Figure 12: *Task Trigger.* E.g., A robot (1) activates the oven when the user requests it; (2) reminds the user of scheduled tasks; (3) detects unusual sounds and navigates within the house to inspect the situation.

D11 **Level of Autonomy** (Figure 13): The extent of independent decision-making in robots is categorised as follows: Fully Directed (follows detailed instructions), Constrained (makes decisions within strict parameters), High (makes most decisions independently), and Adaptive (adjusts decisions based on context or learned preferences). While these categories provide a high-level classification, additional categories may exist, as discussed in the prior work [13, 36, 48, 80]. Autonomy is more critical for mobile robots, as they have greater freedom to act in dynamic environments. For example, in an emergency like a user falling, a stationary device might only call for help, while a mobile robot could assess the situation, seek external assistance, and proactively prepare the environment by opening doors for emergency responders.

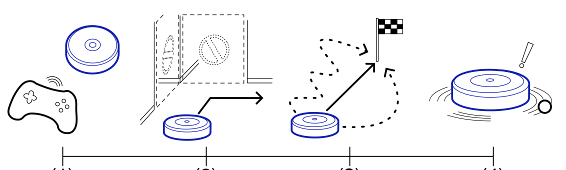


Figure 13: *Level of Autonomy*. E.g., A robot (1) is positioned by the user using a joystick; (2) organises household items to prespecified locations; (3) fetches all necessary ingredients from the fridge based on a high-level user request, like "cooking pasta"; (4) detects and responds to an emergency of a user.

D12 **Interaction Outcomes** (Figure 14): The outcomes of robot interactions can be measured across several sub-dimensions: physical modifications to the [65], information provision [51], communication exchanges [96], the production of tangible goods (e.g., preparing meals [89]), and alterations to the status of an entity. Although static devices can deliver information and facilitate communication, physical modifications, especially at scale (e.g., reconfiguring partition walls), are uniquely enabled by a robot's mobility.

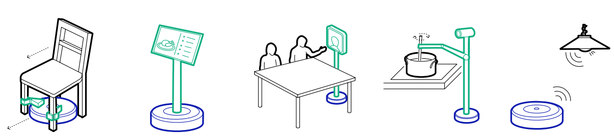


Figure 14: *Interaction Outcomes*. E.g., A robot (1) moves heavy furniture; (2) suggests recipes based on scanned fridge contents; (3) facilitates hands-free video calls; (4) cooks and serves popcorn; (5) manages ventilation by automatically opening windows or activating fans to reduce humidity.

5.1 Linkages in the Design Space

Aligned with the core tenets of the Research-through-Design process, where "*artefacts produced in this type of research become design exemplars, providing an appropriate conduit for research findings to easily transfer to the HCI research and practice communities*" [112], the design dimensions presented here serve as foundational elements for developing domestic robot interactions. These dimensions provide a starting point for guiding human-centric applications in ubiquitous computing, helping robots integrate into everyday life and respond to dynamic user needs. In this section, we clarify how these dimensions interrelate while preserving their distinct roles:

Interdependencies Between Dimensions. Some dimensions naturally influence others due to the complexity of robot interactions. For instance, `D4:Human-Robot Relationship` is relevant when `D1:Interaction Entity` involves users, such as in roles where the user acts as a supervisor or collaborator. However, this relationship is not applicable in cases like the Bystander role, where users simply observe interactions between the robot and other entities. `D11:Level of Autonomy` is closely tied to `D10:Task Trigger`; for example, Adaptive Autonomy is typically aligned with event-driven tasks, while Fully Directed autonomy is more suitable for user-initiated tasks. Similarly, `D6:Action Type`—whether physical, digital, or hybrid—depends on the `D5:Intent` of the task. Typically, care-oriented tasks involve physical actions, while educational tasks tend to require digital outputs.

Distinct Yet Complementary Dimensions. All our design dimensions address distinct aspects of interaction, although many are complimentary in nature. For example, `D7:Spatial Scope` refers to the robot's operational area, such as a specific room or the entire home, whereas `D8:User Proximity` concerns the distance between the robot and the user during the task. A robot can operate in specific spaces based on the user's proximity. For example, it may clean the bathroom only when the user is distant or elsewhere in the house, ensuring privacy. Conversely, in the kitchen, it can assist with tasks like meal prep while the user is nearby, allowing for close monitoring.

As with any design framework, future work will focus on refining and empirically validating these dimensions. Critically, this process must involve gathering feedback directly from end-users to ensure the robot's behaviour aligns with their needs and expectations. Future research must also incorporate ethical considerations, particularly user privacy and data security, to ensure that domestic robots enhance daily life while maintaining trust and transparency.

6 Design Space Evaluation

Demonstrating the completeness of the design space in complex robot-user interactions is challenging due to the multitude of dimensions involved. That said, we employ Delamare's approach, which evaluates both the descriptive power of a design space—its ability to capture existing research—and its generative power—identifying unexplored areas that can be filled with novel scenarios [27].

To identify relevant literature, we systematically reviewed CHI and HRI proceedings from January 2014 to September 2024 using the query: Title:((domestic OR home) AND robot). This search yielded 50 papers. After excluding extended abstracts, the corpus

	D1 Interaction Entity				D2 Interaction Scale				D3 Augmentation Approach				D4 Human-Robot Relationship							D5 Intent				D6 Action Types		
	Robot	Devices	Environment	User	1:1	1:m	n:1	n:m	Built-in	Cart	Helmet	Dock	Supervisor	Operator	Bystander	Cooperator	Collaborator	Service Agent	Companion	Task-oriented	Social	Edu./Training	Caregiving	Physical	Hybrid	Digital
(a)	-	●	●	●	●	-	-	-	●	-	-	-	-	-	-	-	●	-	●	-	-	●	-	-	●	-
(b)	-	●	●	●	●	-	-	-	●	-	-	-	-	●	-	-	-	-	●	-	●	-	-	●	-	-
(c)	-	●	-	●	-	-	●	-	●	-	-	-	-	●	-	-	-	-	●	-	●	-	-	-	●	-
(d)	-	-	●	●	●	-	-	-	●	-	-	-	-	-	-	-	-	●	●	●	-	-	-	-	●	-
(e)	-	●	●	●	-	-	●	-	●	-	-	-	-	●	-	-	●	-	●	-	●	●	-	-	●	-
(f)	-	●	-	●	-	-	●	-	●	-	-	-	-	●	-	-	●	●	●	-	●	●	-	-	-	●
(g)	-	-	●	●	-	-	●	-	●	-	-	-	-	-	-	●	-	●	-	-	-	●	-	-	●	-
(h)	-	-	-	●	●	-	-	-	●	-	-	-	-	-	-	-	-	●	-	-	●	-	●	-	●	-

	D7 Spatial Scope					D8 User Proximity				D9 Interaction Modalities				D10 Task Trigger			D11 Task Trigger				D12 Interaction Outcomes				
	User	Object	Particular	Multiple	Entire Home	Close	Nearby	Within House	Distant	Tactile	Visual	Auditory	Olfactory	User-initiated	Time-based	Event-triggered	Fully Directed	Constrained	High	Adaptive	Physical	Info.	Comm.	Products	System State
(a)	-	-	●	-	-	●	-	-	-	-	●	●	-	●	-	-	-	-	●	-	-	-	●	-	●
(b)	-	-	-	-	-	●	-	-	-	-	●	●	-	-	-	-	-	-	-	●	-	-	●	-	-
(c)	-	-	-	●	●	-	-	-	●	-	●	●	-	●	-	-	●	-	-	-	-	-	●	-	-
(d)	-	-	-	-	-	●	-	-	-	●	●	●	-	●	-	-	●	-	-	-	-	-	●	-	●
(e)	-	-	●	-	-	●	-	●	-	●	●	●	-	●	-	-	-	-	-	-	-	-	●	-	-
(f)	-	-	-	-	-	●	●	-	-	-	●	●	-	-	-	-	●	●	-	-	-	-	●	-	●
(g)	-	-	-	-	-	●	-	-	-	●	●	●	-	●	-	-	●	-	-	-	-	-	●	-	-
(h)	-	-	-	-	-	●	-	-	-	●	●	●	-	●	-	-	-	●	-	-	-	●	●	-	-

Table 2: A • denotes the usage of the associated design dimension in the corresponding related work, while a - indicates it is not covered. (a) Michaelis et al. [57]; (b) Pelikan et al. [70]; (c) Boudouraki et al. [16]; (d) Luria et al. [54]; (e) Zhao & McEwen [111]; (f) Ahtinen et al. [3]; (g) Ho et al. [43]; (h) Bouzida et al. [17].

was further refined to include only works mainly focusing on interaction. While not exhaustive, this descriptive selection provides a snapshot of the current landscape. The resulting eight papers, summarised in Table 2, illustrate their association with our 12 design space dimensions, as well as with the sub-dimensions.

In our generative power analysis, we observed that `D3:Augmentation` dimension was notably underrepresented, followed by `D7:Spatial Scope` and `D10:Task Trigger`, in the existing literature. To address this gap, we conceptualised applications for a multifunctional robot vacuum throughout the day while focusing on these dimensions and combined the findings from our survey.

At 6 am, the domestic robot activates and attaches an arm to its frame. It gently taps the user, Taylor, on the shoulder to wake her up. Upon waking, the robot reminds her to take her vitamin supplements. At 7 am, the robot checks the status of the indoor plants. Noticing that the leaves have started to wilt, it attaches an arm and several carts to itself, then transports the plants to the deck to be placed in the sunlight. According to our survey findings, the robot typically begins cleaning the house at 10 am and takes approximately two hours. The robot finishes cleaning by 12 pm and proceeds to charge for the next four hours. By 4 pm, the robot is fully charged. It then reattaches the arm and carts and retrieves the indoor plants from the deck, bringing them back inside. At 6 pm, Taylor begins cooking and asks the robot for a recipe. In response, the robot attaches a projector to itself, displaying the recipe on the kitchen wall, allowing Taylor to follow the instructions hands-free. Once cooking is completed, the robot autonomously inspects the kitchen to ensure the stove and chimney are turned off for Taylor's safety. Later, at 11 pm, when Taylor falls asleep, the robot enters silent-mode. It quietly scans the house for security purposes, ensuring that doors and windows are secure. Simultaneously, it performs a quick house maintenance check, monitoring for any potential issues such as water leaks or electrical malfunctions. By midnight, the robot completes its final task—checking for condensation on the walls and floors, particularly under furniture, ensuring a safe and dry environment.

This scenario illustrates how the domestic robot seamlessly integrates into daily routines, providing practical assistance for health, security, and house maintenance while enhancing the user experience through proactive tasks. Future work can leverage technologies such as Large Language Models (LLMs) to create even more novel applications [90], building upon the twelve dimensions as design constraints and the application cases (illustrated in Section 7) as a starting point.

7 Application Use Cases

In Section 4.3, the thematic analysis of the interviews also revealed insights into addressing our RQ3: "What additional functions can domestic cleaning robots perform during idle periods?" Through an iterative process, we categorised the identified use cases into eight distinct themes: Home maintenance and management (29 use cases), personal assistance (27), health and wellness (12), food preparation and dining (13), communication and social interaction (8), pet care (6), security (5), and entertainment (4). As illustrated in Figure 15, we present a curated list of 104 unique application use cases. This contribution provides a substantial resource for shaping both theoretical research questions, as well as practical pathways for the future development of domestic robots.

Although most of our applications can be performed at any time of day due to their nature and the generalisation during the thematic analysis, participants expressed that certain applications are more suitable for specific times of the day. For instance, in the morning, one participant suggested: "*[If I had the robot, I'd] like a SAD lamp attachment so it could wake you up*" (P11), while another mentioned: "*[The robot performs] cleaning up my bed, doing my bed sheets, all that stuff I have to do in the morning*" (P12). During the daytime, a participant remarked: "*If you could imagine these robots following you around . . . it could do things like, 'hey, this person is busy'*" (P2). Both P1 and P7 highlighted their need for robot assistance during dinner time: "*Before making dinner . . . [the robot] could stick some potatoes in the oven*" (P1) and "*For dinner, . . . it can bring me some pepper or salt*" (P7). At night, one participant commented: "*[The robot and my niece] can do a bedtime together, but then she can listen to a bedtime story . . . So I can sort of see some of the benefits*" (P1). Additionally, another participant expressed interest in automatic tracking: "*Tracking automatic [sleep] tracking at one place. I would love that*" (P4).

These examples highlight how different tasks can be tailored to specific times of the day (e.g., medicine reminders). On the other hand, it is also clear that tasks—such as responding to emergencies, correcting posture, controlling lights and AC, opening doors, and fetching items—can be performed flexibly throughout the day.

8 Proof-of-Concept System

We created four distinct proof-of-concept applications (see Figure 16 and the video figure) to substantiate the feasibility of repurposing domestic robots for a range of interactions in everyday contexts. These demonstrations serve as 'existence proofs' of our approach, in line with the evaluation methods proposed by Ledo et al. [50]. These applications were informed by the application scenarios generated during our expert interviews, showcasing the diverse roles a robot can play throughout the day.

8.1 Demonstrations

We implemented the proof-of-concept prototypes using the Create 3 all-in-one mobile robot development platform by iRobot, which includes obstacle sensors and an odometric sensor according to its datasheet[13]. Although similar to the Roomba Combo Essential Robot, the Create 3 does not include vacuuming and mopping functions. However, it allows the integration of additional input and output modalities that we leveraged to build our demonstrations. To operate the prototype, we included a Raspberry Pi 5 (powered by the Create 3's payload power). Since Raspberry Pi requires 5.1V while the payload supplies 14.4V, we employed a DC-DC buck converter (CK1408) to regulate the voltage. Note that the Raspberry Pi handles sensor data acquisition and communicates with a server for processing. The server on a Windows Laptop performs computations, including machine-learning model inference, and sends instructions back to the Raspberry Pi. The Raspberry Pi controls the robot and actuators via Bluetooth Low Energy and communicates with the server over Wi-Fi (TCP).

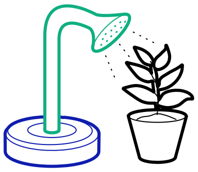
8.1.1 Serving as a mobile wireless charger. The functionality of a mobile charger can be integrated into the robot. The robot is designed to follow a user when required, and the user can charge their smartphone by simply placing it on the charging spot on the robot. The user is not required to search for an available mains supply or carry a mobile battery to charge the phone. In this application (Figure 16(1)), we designed and 3D printed a re-configurable mount to place on the top of the prototype (shown in green). We reused components in a wireless charger stand and created the charging stand to attach to the mount. This functionality can be used at any time when the user needs to charge their phone, such as during activities like breakfast or other daily routines.

8.1.2 Showing a user's busy status. An additional display enables the robot to undertake a variety of tasks. To illustrate, during the daytime when a user starts a video meeting, the robot can indicate a message from a user, such as "Meeting in Progress, Do not Disturb", when the user starts a video meeting. The robot then notifies the relevant individuals, such as the user's children, and provides the user with a quiet environment to work. To implement this application (Figure 16(2)), we installed a screen with a stand onto the designed mount and used a tablet device that displays the message.

8.1.3 Projecting workout videos on the wall. An alternative configuration would be to attach a projector to the robot in place of the screen. Such an application could be the presentation of a video of a fitness lecture, which could assist a user in replicating the exercises demonstrated by a fitness instructor. The projector's flexibility in terms of direction allows the robot to enable the user to view the video from a variety of positions. For example, the video is projected onto a wall when the user is upright and onto the ceiling when the user is lying down. This application is particularly useful

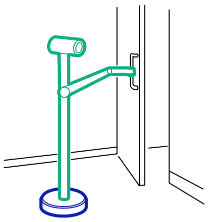
[13]https://experience.irobot.com/hubfs/Create%203/Create-3_DataSheet.pdf

Home Maintenance & Management (29)



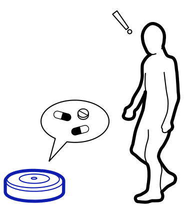
Clears and sorts food waste while meal is being prepared; Collects and disposes of general household rubbish and takes out the trash; Assists with laundry: transfers, hangs, folds, stores clothes, and sorts by colour; Organizes and tidies up household items, including small items and dog toys; Waters indoor plants; Sorts recyclable materials from waste; Collects used plates, rinses, and places them in the dishwasher; Dusts surfaces; Dries items; Helps with making the bed; Reminds users to take out the trash; Moves plants for sunlight; Adjusts furniture; Manages conditions of valuable goods; Controls lights and pre-activates AC; Diffuses scent around guests; Manages ventilation by automatically opening windows or activating fans to prevent humidity; Directs heat and airflow at the user during various activities; Checks if the user is free during tasks and suggests additional tasks (e.g., washing dishes while cooking); Moves clutter during cooking; Empties dehumidifier by taking it to the sink; Monitors home appliances to share their task progress; Informs user about home items maintenance needs; Serves as a mobile wireless charger for devices; Interacts with heating based on user activity; Monitors user activity and provides power optimization; Acts as sensor suite for smart home integration; Acts as portable heater, dehumidifier, or lamp, Detects and alerts user for humidity, temperature, or mold

Personal Assistance (27)



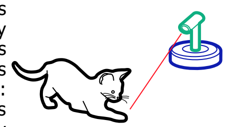
Baby Monitoring; Walking Support; Facilitates communication across multiple rooms/floors; Reduces interruptions by showing user's busy status; Assists with video production; Takes notes while performing another activity; Tracks daily activities (e.g., water intake); Clears paths and alerts for tripping hazards; Provides hydration and nourishment during study or other cognitively demanding activities; Opens and closes doors for improved access; Assists while climbing stairs; Helps carry groceries or items from the supermarket; Serves as a mobile alarm clock, Receives and delivers packages when the user is busy; Fetches drinks, snacks, or items from the fridge, or other items like paper from printer; Dries hair; Assists with picking clothes; Provides proper screen view during various daily activities, like cooking, showering, gardening, playing musical instruments etc.; Reduces distractions by temporarily hiding the user's phone; Provides non-intrusive reminders for upcoming meetings, Recognizes user's activity and activates relevant music or podcast; Assists with 3D printing tasks, such as managing prints, checking vibrations, and removing plates; Retrieves items for garden tasks, Projects shortcuts and documents during video calls; Holds and manipulates objects, like a soldering iron or tools while building furniture; Locates and collects dropped or misplaced items; Acts as an accountability partner for scheduled tasks, providing gentle reminders

Health & Wellness (12)



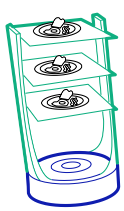
Tracks and reminds about medication; Collaborates with other devices for sleep tracking; Encourages user to move and walk around; Acts as a variable weight exercise equipment; Acts as a pet-like companion for emotional support; Bedtime Story Assistant; Projects workout videos on the wall; Provides mobile light therapy with a SAD lamp; Detects and responds to emergencies like a fallen person; Assists with exercise: supports limbs, corrects posture, and prevents injuries; Corrects posture; Provides sensory feedback by rubbing user with materials

Pet Care (6)



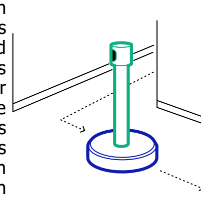
Dispenses treats remotely with user confirmation; Reminds and assists with monthly flea repellant treatment; Entertains pets with videos, lasers, music, moving; Prevents pets from entering specific rooms or zones in house; Monitors pets; Cleans pet items like litter boxes and bowls

Food Preparation & Dining (13)



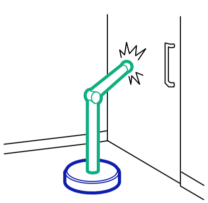
Keeps food hot or cools it down using airflow; Assists with cooking by extending workspace and holding items; Makes drinks like coffee or cocktails; Monitors food condition and detects spoilage; Checks fridge and reminds or buys ingredients based on meal choices; Prepares ingredients for meals; Suggests recipes based on scanned fridge contents; Distributes food (with family or visitors); Cooks meals like popcorn or places potatoes in oven; Brings items like pepper or salt during dinner; Brings breakfast in bed; Activates oven's pre-heat during cooking, Assistance with opening jars

Security (5)



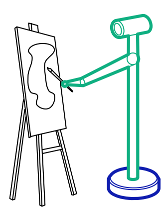
Allows remote monitoring and task control of home with live video; Performs home security patrols; Monitors garage door status; Monitors windows, closes them automatically if intrusion or rain is expected; Identifies unusual sounds and navigates to the source

Communication & Social Interaction (8)



Answers the door, communicates with visitors, and relays messages; Provides hands-free video calls by following the user; Notifies the family members when meal is ready by knocking on doors; Initiates social calls to friends or family; Breaks the ice with jokes and interactions, Projects voice onto objects for directed audio notifications; Interrupts subtly, respecting privacy; Explains actions via a display

Entertainment (4)



Demonstrates tasks like cooking and drawing using an articulated arm; Helps practice dance moves through kinesthetic interaction;
Multiple robots collaborate to create a 4D sound experience;
Plays music and generates physical sounds

Figure 15: List of 104 applications use cases derived from our expert interviews.

Figure 16: Implemented Applications: (1) The robot serves as a mobile wireless charger. The robot follows the user, and the user can charge the phone by placing it in the holder, (2) The robot shows the user's busy status using the attached screen, (3) The robot projects a workout video on the wall (Left) and on the ceiling (Right), (4) The user monitors the home remotely and has task control of the home with live video. The robot observes the oven (Left), and the user watches the live video and controls the robot (Right).

in the evening, when the user may want to relax and follow a workout routine at home. As shown in Figure 16(3), we designed a 3D printed connector for the Picopix Projector (PPX4935) by Philips to mount on the robot. The angle of the projector is automatically adjusted by reeling a string linked to the connectors.

8.1.4 Remote monitoring and task control of home with live video. Understanding visual information is crucial for monitoring and enables a robot to perform remote home surveillance when combined with user control. The robot captures indoor images, and streams live video to the user, who can manipulate the robot remotely while viewing the real-time feed. For example, during the daytime or when the user is away, they can check if the oven is left on by directing the robot to the kitchen and watching the video feed from another location. Additionally, if the robot connects with IoT appliances like lights or heating systems, the user can control them via the robot. To demonstrate this application, we developed a camera module that installs into the robot and provides three degrees of freedom (as shown in Figure 16(4)). We achieve lifting with a pantograph mechanism driven by a stepping motor (CX28BYJ48) connected to the GPIO pins on the Raspberry Pi through a stepping motor driver (ULN2003). Two servo motors (SM-S2309S) control the camera angle, and we attach the Raspberry Pi Camera Module 3 Wide to the designated port. We also expand the hole on the Create 3's top board to allow the camera module to extend. We use the Python library Flet to create a graphical user interface, enabling users to view the image and control the robot via the keyboard.

9 Discussion and Future Work

In this paper, we take an exploratory approach to investigate how idle time in domestic robots can be effectively utilised. Through expert interviews and thematic analysis, we uncover 12 critical design dimensions and propose novel use cases that leverage the unique mobility and interaction capabilities of robots. These findings extend beyond traditional robotic tasks, opening new possibilities for human-robot interaction in domestic settings. Building on these insights, we now reflect on our findings, discuss their implications for HCI and HRI research, and outline avenues for future work to enhance the design and functionality of domestic robots.

9.1 Extending the Design Space and Use Cases

The expert perspectives we gathered lay a foundational groundwork for building interactions with domestic robots. As with other frameworks of this kind, we anticipate further development and refinement of these considerations, including:

9.1.1 Form-Factor Considerations. As domestic robotics continues to evolve, the implications of form-factor design become increasingly critical. Previous studies have highlighted positive user attitudes toward robots, with a distinct preference for non-humanoid designs [9, 25, 47]. While our study focuses on a vacuum-based robot form factor, it is important to acknowledge that some applications, such as a bedtime story assistant, do not necessarily require mobility and could be implemented on stationary or semi-mobile devices. Following this, Our survey found that most users prefer placing robots in the living room, offering an opportunity to create versatile robots optimised for this environment. Incorporating hot-swappable attachments or flexible designs, like those in soft robotics, could enhance adaptability without sacrificing mobility. It is crucial that these features don't impede navigation, allowing robots to access hard-to-reach areas, such as under the sofa, to maintain functionality and approachability in different environments.

9.1.2 Multi-Modal Interaction. Experts consistently emphasised the need for diverse communication methods, including voice commands, non-verbal cues, and manual controls. This underscores the importance of flexibility in interaction modalities. For instance, combining physical gestures with voice commands could improve usability in situations where hands-free or silent communication is preferred. Future work should focus on evaluating multi-modal interactions that integrate various communication methods between robots and humans.

9.1.3 Prioritising Routine and Repetitive Tasks. Experts frequently expressed a desire for robots to automate repetitive or tedious tasks, such as laundry and waste management. While there is strong interest in having robots manage these routine chores to save time and increase efficiency, experts also indicated a preference for not delegating all household tasks to robots. This suggests that designers should focus on developing robots that excel at specific repetitive tasks while maintaining a balance between automation and user engagement. Future research should explore additional routine tasks suitable for automation and investigate how to best integrate robotic assistance with human involvement to maximise the utility and acceptance of domestic robots.

9.1.4 Health-Related Assistance. There was a strong interest in robots that support health and well-being, such as those that remind users about medication or ensure home safety, like drying slippy bathroom floors. Prioritising these features, especially for users with specific accessibility needs, is essential. Future work should explore integrating advanced health-monitoring and assistance functionalities, making domestic robots vital tools for maintaining user health and well-being.

9.1.5 Respecting Physical and Social Boundaries. Participants highlighted the importance of robots respecting physical and social boundaries, such as avoiding interruptions during family rituals or meals. This feedback should guide designers in addressing the Interaction Entity and Interaction Scale dimensions, ensuring robots complement rather than disrupt human social norms. Future studies could investigate how robots can respect and integrate into these boundaries, minimising disruption and discomfort.

9.1.6 Understanding Diverse Housing Needs. During our interviews, we noticed that where people lived had a big impact on the types of tasks they preferred. For example, people in cities or small apartments liked tasks that saved space, while those in suburbs or larger homes were more focused on overall maintenance. This shows that where people live affects what tasks they prioritise, and this can lead to different results depending on the type of housing. Recognising these differences is important for creating robots for the home that can meet the diverse needs of people in different living situations.

9.2 Autonomy and Task Management

Balancing autonomy and control is crucial for deploying domestic robots effectively. Experts emphasised this balance and highlighted additional task-allocation factors critical for future designs.

9.2.1 Autonomy with User Control. Many participants value robots that can autonomously complete tasks but also desire control over key functions. They prefer permission-based systems where robots seek consent before performing specific tasks, especially in sensitive situations. This indicates the need for a flexible autonomy framework, allowing robots to switch between autonomous and user-directed modes as required. Future research should focus on developing adaptive autonomy frameworks that offer users control options, which will align robots' tasks with user comfort and trust.

9.2.2 Environmental Adaptation. Domestic robots must possess the capability to adapt to varying home layouts, including navigating stairs, opening and closing doors, and efficiently operating within compact spaces. This requirement highlights the need for context-aware behaviour, where robots adjust their operations based on the physical environment and user preferences. Designers should consider context-aware adaptation techniques to allow robots to operate effectively in diverse settings for improved functionality and safety.

9.2.3 Privacy and Data Protection. Privacy concerns remain significant, particularly for robots operating in intimate areas like bedrooms or bathrooms. Users expect robots to protect personal data and respect spatial privacy. Therefore, designers must incorporate strong privacy safeguards, contextual awareness, and data protection mechanisms [99]. Additionally, robots should maintain appropriate physical proximity to avoid discomfort or breaches of personal space. Future studies should focus on developing robust privacy and data protection mechanisms to build user trust and ensure comfort in personal spaces.

9.2.4 Dynamic Task Allocation. Effective dynamic task allocation is a key challenge. As robots take on more roles at home, systems must intelligently assign tasks based on user needs and contexts.

For example, a robot might prioritise meal preparation tasks during cooking times but switch to managing family schedules afterwards. This balance requires careful management of the robot's autonomy and role distribution. Future research should focus on dynamic task allocation frameworks that adapt to evolving user needs and contexts, such that robots could deliver personalised and efficient assistance to users.

9.3 Limitations

Our study demonstrates how repurposing a robot's idle time and mobility can enable new applications in ubiquitous computing. Yet, there are certain limitations, which we outline below, along with possible directions for future work.

First, we used an expert ideation approach to systematically develop a multi-dimensional design space. However, relying solely on professional input risks overlooking the nuanced needs of end-users, potentially misaligning designs with real-world expectations. To address this, future work should incorporate direct user input through participatory design sessions and co-creation workshops. This would ensure future domestic robots cater to different personalised user needs and home layouts.

Second, while focusing on routine tasks provided structure during the interviews, it may have limited exploration of unconventional or personalised tasks. Additionally, participants' routines influenced their contributions; those who did not work from home offered fewer insights due to limited interaction with home-based activities. These limitations highlight the need for future research to include a more diverse participant pool and expand the scope to cover a wider range of household tasks.

Finally, while our proof-of-concept system demonstrates the feasibility of the design space through four applications, it has not yet undergone extensive user testing or real-world evaluation. Without end-user feedback, assessing the practical viability and effectiveness of these designs remains challenging. Future research should evaluate these applications with end-users in their actual homes to better understand practical challenges and opportunities. This includes exploring technical solutions such as integrating advanced sensing technologies, incorporating dynamic actuation techniques (e.g., adjustable periscopes), and developing optimal mapping and navigation strategies to expand functionality and address a broader range of tasks.

10 Conclusion

As domestic robots increasingly integrate into our daily lives, exploring their full potential becomes essential. This paper introduces a novel approach by investigating how we can repurpose the idle times of these robots for tasks beyond their primary functions. We base our idea on the fact that many existing robots already have advanced sensors, which can provide security and environmental monitoring during inactivity. Our survey with 50 robot vacuum cleaner users provides an initial context for exploring extra functionalities during their substantial idle periods. We found that 40% of users activate their vacuum cleaners only once a day, primarily between 7 AM and 11 AM. This usage pattern points to an opportunity for more efficient use of these robots during their downtime. Through interviews with HCI and HRI experts (n=12), we developed a comprehensive design space with 12 dimensions to help designers and engineers create novel ubiquitous computing interactions. We also identified over 100 potential applications, illustrating how to expand domestic robots beyond their traditional roles. Our proof-of-concept system, which implemented four working applications, shows the technical feasibility. Our findings demonstrate that domestic robots can significantly improve and support modern lifestyles when viewed from a broader perspective. Future research should focus on refining these design dimensions with end-users, integrating sensing and actuation functionalities, and exploring other novel applications to fully utilise domestic robots' potential in everyday contexts.

Acknowledgments

We are very grateful to our survey participants and, in particular, to the expert interviewees who generously shared their time and insights. We express our sincere appreciation to Alvaro Favaratto Santos for his help in circuit designing and 3D printing. Additionally, we thank the anonymous reviewers for their valuable feedback. Finally, we acknowledge the support of both the Natural Sciences and Engineering Research Council of Canada (NSERC: RGPIN-2023-03608) and the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (FORCE-UI, Grant agreement No. 853063) for partly funding this research.

References

[1] Muneeb Ahmad, Omar Mubin, and Joanne Orlando. 2017. A systematic review of adaptivity in human-robot interaction. *Multimodal Technologies and Interaction* (2017). https://doi.org/10.3390/mti1030014

[2] Michael Ahn, Anthony Brohan, Noah Brown, Yevgen Chebotar, Omar Cortes, Byron David, Chelsea Finn, Chuyuan Fu, Keerthana Gopalakrishnan, Karol Hausman, Alex Herzog, Daniel Ho, Jasmine Hsu, Julian Ibarz, Brian Ichter, Alex Irpan, Eric Jang, Rosario Jauregui Ruano, Kyle Jeffrey, Sally Jesmonth, Nikhil J. Joshi, Ryan Julian, Dmitry Kalashnikov, Yuheng Kuang, Kuang-Huei Lee, Sergey Levine, Yao Lu, Linda Luu, Carolina Parada, Peter Pastor, Jornell Quiambao, Kanishka Rao, Jarek Rettinghouse, Diego Reyes, Pierre Sermanet, Nicolas Sievers, Clayton Tan, Alexander Toshev, Vincent Vanhoucke, Fei Xia, Ted Xiao, Peng Xu, Sichun Xu, Mengyuan Yan, and Andy Zeng. 2022. Do As I Can, Not As I Say: Grounding Language in Robotic Affordances. https://doi.org/10.48550/arXiv.2204.01691

[3] Aino Ahtinen, Nasim Beheshtian, and Kaisa Väänänen. 2023. Robocamp at Home: Exploring Families' Co-Learning with a Social Robot: Findings from a One-Month Study in the Wild. In *Proceedings of the 2023 ACM/IEEE International Conference on Human-Robot Interaction (HRI '23)*. https://doi.org/10.1145/3568162.3576976

[4] Gerd Bruder Alexis Lambert, Nahal Norouzi and Gregory Welch. 2020. A Systematic Review of Ten Years of Research on Human Interaction with Social Robots. *International Journal of Human–Computer Interaction* (2020). https://doi.org/10.1080/10447318.2020.1801172

[5] Ferran Altarriba Bertran, Elena Márquez Segura, Jared Duval, and Katherine Isbister. 2019. Chasing Play Potentials: Towards an Increasingly Situated and Emergent Approach to Everyday Play Design. In *Proceedings of the 2019 on Designing Interactive Systems Conference (DIS '19)*. Association for Computing Machinery. https://doi.org/10.1145/3322276.3322325

[6] Aloha Hufana Ambe, Margot Brereton, Alessandro Soro, Laurie Buys, and Paul Roe. 2019. The Adventures of Older Authors: Exploring Futures through Co-Design Fictions. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)*. Association for Computing Machinery. https://doi.org/10.1145/3290605.3300588

[7] Sean Andrist, Xiang Zhi Tan, Michael Gleicher, and Bilge Mutlu. 2014. Conversational gaze aversion for humanlike robots. In *Proceedings of the 2014 ACM/IEEE international conference on human-robot interaction (HRI '14)*. https://doi.org/10.1145/2559636.2559666

[8] Kika Arias, Sooyeon Jeong, Hae Won Park, and Cynthia Breazeal. 2020. Toward Designing User-Centered Idle Behaviors for Social Robots in the Home. In

1st International Workshop on Designerly HRI Knowledge. Held in Conjunction with the 29th IEEE International Conference on Robot and Human Interactive Communication (RO-MAN 2020). https://malulu.github.io/HRI-Design-2020/assets/pdf/Arias%20et%20al.pdf

[9] Kai O Arras and Daniela Cerqui. 2005. Do we want to share our lives and bodies with robots? A 2000 people survey: a 2000-people survey. *Technical report* (2005). https://doi.org/10.3929/ethz-a-010113633

[10] Thibault Asselborn, Wafa Johal, and Pierre Dillenbourg. 2017. Keep on moving! Exploring anthropomorphic effects of motion during idle moments. In *2017 26th IEEE international symposium on robot and human interactive communication (RO-MAN).* https://doi.org/10.1109/ROMAN.2017.8172409

[11] Seung-Ho Baeg, Jae-Han Park, Jaehan Koh, Kyung-Wook Park, and Moon-Hong Baeg. 2007. Building a smart home environment for service robots based on RFID and sensor networks. In *2007 International Conference on Control, Automation and Systems (ICCAS '07).* https://doi.org/10.1109/ICCAS.2007.4407059

[12] Jimmy Baraglia, Maya Cakmak, Yukie Nagai, Rajesh Rao, and Minoru Asada. 2016. Initiative in Robot Assistance during Collaborative Task Execution. In *The Eleventh ACM/IEEE International Conference on Human Robot Interaction (HRI '16).* https://doi.org/10.1109/HRI.2016.7451735

[13] Jenay M Beer, Arthur D Fisk, and Wendy A Rogers. 2014. Toward a framework for levels of robot autonomy in human-robot interaction. *J. Hum.-Robot Interact.* (2014). https://doi.org/10.5898/JHRI.3.2.Beer

[14] Mohd Zikrul Hakim bin Noor, Mohd Syafiq bin Mohd Zainuddin, Muhammad Farid bin Saaid, and Megat Syahirul Amin bin Megat Ali. 2012. Design and conceptual development of a sunbathe laundry robot. In *2012 IEEE 8th International Colloquium on Signal Processing and its Applications.* https://doi.org/10.1109/CSPA.2012.6194736

[15] Andrea J Bingham and Patricia Witkowsky. 2022. Deductive and inductive approaches to qualitative data analysis. *Vanover C, Mihas P, Saldaña Jeditors. Analyzing and Interpreting Qualitative Data: After the Interview. SAGE Publications* (2022).

[16] Andriana Boudouraki, Stuart Reeves, Joel E Fischer, and Sean Rintel. 2022. Mediated Visits: Longitudinal Domestic Dwelling with Mobile Robotic Telepresence. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems (CHI '22).* Association for Computing Machinery. https://doi.org/10.1145/3491102.3517640

[17] Anya Bouzida, Alyssa Kubota, Dagoberto Cruz-Sandoval, Elizabeth W. Twamley, and Laurel D. Riek. 2024. CARMEN: A Cognitively Assistive Robot for Personalized Neurorehabilitation at Home. In *Proceedings of the 2024 ACM/IEEE International Conference on Human-Robot Interaction (HRI '24).* https://doi.org/10.1145/3610977.3634971

[18] Virginia Braun and Victoria Clarke. 2012. Thematic analysis. In *APA handbook of research methods in psychology, Vol 2: Research designs: Quantitative, qualitative, neuropsychological, and biological.* American Psychological Association. https://doi.org/10.1037/13620-004

[19] A.J. Bernheim Brush, Bongshin Lee, Ratul Mahajan, Sharad Agarwal, Stefan Saroiu, and Colin Dixon. 2011. Home automation in the wild: challenges and opportunities. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11).* https://doi.org/10.1145/1978942.1979249

[20] Guido Bugmann and Simon N. Copleston. 2011. What Can a Personal Robot Do for You?. In *Towards Autonomous Robotic Systems*, Roderich Groß, Lyuba Alboul, Chris Melhuish, Mark Witkowski, Tony J. Prescott, and Jacques Penders (Eds.). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-23232-9_32

[21] Maya Cakmak and Leila Takayama. 2013. Towards a comprehensive chore list for domestic robots. In *Proceedings of the 8th ACM/IEEE International Conference on Human-Robot Interaction (HRI '13).* https://doi.org/10.1109/HRI.2013.6483517

[22] Haena Cho, Gurim Kim, and Chang Hee Lee. 2024. Olfactory Puppetry: Merging Olfaction and Puppetry to Explore the Future of Olfactory Social Robots. In *Proceedings of the 2024 ACM Designing Interactive Systems Conference (DIS '24).* https://doi.org/10.1145/3643834.3660733

[23] C. Hummert D. Pawlaszczyk, J. Friese. 2019. "Alexa, tell me …" - A forensic examination of the Amazon Echo Dot 3 rd Generation. *International Journal of Computer Sciences and Engineering* (2019). https://doi.org/10.26438/ijcse/v7i11.2029

[24] Ella Dagan, James Fey, Sanoja Kikkeri, Charlene Hoang, Rachel Hsiao, and Katherine Isbister. 2020. Flippo the Robo-Shoe-Fly: A Foot Dwelling Social Wearable Companion. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems (CHI EA '20).* Association for Computing Machinery. https://doi.org/10.1145/3334480.3382928

[25] K. Dautenhahn, S. Woods, C. Kaouri, M.L. Walters, Kheng Lee Koay, and I. Werry. 2005. What is a robot companion - friend, assistant or butler?. In *2005 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS '05).* https://doi.org/10.1109/IROS.2005.1545189

[26] Essam Debie, Kathryn Kasmarik, and Matt Garratt. 2023. Swarm Robotics: A Survey from a Multi-Tasking Perspective. *Comput. Surveys* (2023). https://doi.org/10.1145/3611652

[27] William Delamare, Céline Coutrix, and Laurence Nigay. 2015. Designing guiding systems for gesture-based interaction. In *Proceedings of the 7th ACM SIGCHI Symposium on Engineering Interactive Computing Systems (EICS '15).* https://doi.org/10.1145/2774225.2774847

[28] Maja Dybboe, Johannes Ellemose, Alexander Langagergaard Vastrup, Andriana Boudouraki, Sean Rintel, Marianne Graves Petersen, Jens Emil Sloth Grønbæk, and Clemens Nylandsted Klokmose. 2024. TableBot: Getting a Handle on Hybrid Collaboration by Negotiating Control of a Tabletop Telepresence Robot. In *Proceedings of the 13th Nordic Conference on Human-Computer Interaction (NordiCHI '24).* Association for Computing Machinery. https://doi.org/10.1145/3679318.3685350

[29] Mohan Rajesh Elara, Nicolas Rojas, and Adrian Chua. 2014. Design principles for robot inclusive spaces: A case study with Roomba. In *2014 IEEE International Conference on Robotics and Automation (ICRA '14).* https://doi.org/10.1109/ICRA.2014.6907681

[30] Abrar Fallatah, Brett Stoddard, Margaret Burnett, and Heather Knight. 2021. Towards user-centric robot furniture arrangement. In *2021 30th IEEE International Conference on Robot & Human Interactive Communication (RO-MAN) (RO-MAN '21).* https://doi.org/10.1109/RO-MAN50785.2021.9515552

[31] David Fischinger, Peter Einramhof, Konstantinos Papoutsakis, Walter Wohlkinger, Peter Mayer, Paul Panek, Stefan Hofmann, Tobias Koertner, Astrid Weiss, Antonis Argyros, and Markus Vincze. 2016. Hobbit, a care robot supporting independent living at home: First prototype and lessons learned. *Robotics and Autonomous Systems* (2016). https://doi.org/10.1016/j.robot.2014.09.029

[32] Terrence Fong, Illah Nourbakhsh, and Kerstin Dautenhahn. 2003. A survey of socially interactive robots. *Robotics and Autonomous Systems* (2003). https://doi.org/10.1016/S0921-8890(02)00372-X

[33] Jodi Forlizzi. 2007. How robotic products become social products: an ethnographic study of cleaning in the home. In *Proceedings of the ACM/IEEE International Conference on Human-Robot Interaction (HRI '07).* https://doi.org/10.1145/1228716.1228734

[34] Jodi Forlizzi and Carl DiSalvo. 2006. Service robots in the domestic environment: a study of the roomba vacuum in the home. In *Proceedings of the 1st ACM SIGCHI/SIGART Conference on Human-Robot Interaction (HRI '06).* https://doi.org/10.1145/1121241.1121286

[35] Randy Gomez, Deborah Szapiro, Kerl Galindo, and Keisuke Nakamura. 2018. Haru: Hardware Design of an Experimental Tabletop Robot Assistant. In *Proceedings of the 2018 ACM/IEEE International Conference on Human-Robot Interaction (HRI '18).* https://doi.org/10.1145/3171221.3171288

[36] Michael A. Goodrich, Timothy W. McLain, Jeffrey D. Anderson, Jisang Sun, and Jacob W. Crandall. 2007. Managing autonomy in robot teams: observations from four experiments. In *Proceedings of the ACM/IEEE International Conference on Human-Robot Interaction (HRI '07).* https://doi.org/10.1145/1228716.1228721

[37] Michael A. Goodrich and Alan C. Schultz. 2008. Human–robot interaction: a survey. *Foundations and Trends® in Human–Computer Interaction* (2008). https://doi.org/10.1561/1100000005

[38] Horst-Michael Gross, Steffen Mueller, Christof Schroeter, Michael Volkhardt, Andrea Scheidig, Klaus Debes, Katja Richter, and Nicola Doering. 2015. Robot Companion for Domestic Health Assistance: Implementation, Test and Case Study under Everyday Conditions in Private Apartments. In *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS '15).* https://doi.org/10.1109/IROS.2015.7354230

[39] Cheng Guo and Ehud Sharlin. 2008. Exploring the use of tangible user interfaces for human-robot interaction: a comparative study. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '08).* Association for Computing Machinery. https://doi.org/10.1145/1357054.1357076

[40] Isla Xi Han and Sarah Witzman. 2023. Internet of Robotic Cat Toys to Deepen Bond and Elevate Mood. In *Companion of the 2023 ACM/IEEE International Conference on Human-Robot Interaction (HRI '23).* https://doi.org/10.1145/3568294.3580183

[41] Jeonghye Han, Miheon Jo, Sungju Park, and Sungho Kim. 2005. The educational use of home robots for children. In *ROMAN 2005. IEEE International Workshop on Robot and Human Interactive Communication, 2005.* https://doi.org/10.1109/ROMAN.2005.1513808

[42] Sascha Herr, Tom Gross, Michael Gradmann, and Dominik Henrich. 2016. Exploring Interaction Modalities and Task Allocation for Household Robotic Arms. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '16).* Association for Computing Machinery. https://doi.org/10.1145/2851581.2892456

[43] Hui-Ru Ho, Edward M. Hubbard, and Bilge Mutlu. 2024. "It's Not a Replacement:" Enabling Parent-Robot Collaboration to Support In-Home Learning Experiences of Young Children. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems (CHI '24).* Association for Computing Machinery. https://doi.org/10.1145/3613904.3642806

[44] Yuhan Hu and Guy Hoffman. 2019. Using skin texture change to design emotion expression in social robots. In *Proceedings of the 14th ACM/IEEE International Conference on Human-Robot Interaction (HRI '19).* https://doi.org/10.1109/HRI.2019.8673012

[45] Sung JaYoung, Rebecca E Grinter, and Henrik I Christensen. 2010. Domestic robot ecology. *International journal of social robotics* (2010).

[46] Changan Jiang, Shinya Hirano, Toshiharu Mukai, Hiromichi Nakashima, Kazuya Matsuo, Dapeng Zhang, Hadi HONARVAR, Tatsuya Suzuki, Ryojun Ikeura, and Shigeyuki Hosoe. 2015. Developmentof High-functionality Nursing-care AssistantRobot ROBEAR for Patient-transfer and Standing Assistance. *Proceedings of the 2015 JSME Conference on Robotics and Mechatronics* (2015). https://doi.org/10.1299/jsmermd.2015._2A2-U06_1

[47] Zayera Khan. 1998. Attitudes towards intelligent service robots. *IPL Technical Report* (1998). https://cir.nii.ac.jp/crid/1571980074994210816

[48] Stephanie Kim, Jacy Reese Anthis, and Sarah Sebo. 2024. A Taxonomy of Robot Autonomy for Human-Robot Interaction. In *Proceedings of the 2024 ACM/IEEE International Conference on Human-Robot Interaction (HRI '24)*. https://doi.org/10.1145/3610977.3634993

[49] Amy Koike and Bilge Mutlu. 2023. Exploring the Design Space of Extra-Linguistic Expression for Robots. In *Proceedings of the 2023 ACM Designing Interactive Systems Conference (DIS '23)*. https://doi.org/10.1145/3563657.3595968

[50] David Ledo, Steven Houben, Jo Vermeulen, Nicolai Marquardt, Lora Oehlberg, and Saul Greenberg. 2018. Evaluation Strategies for HCI Toolkit Research. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. Association for Computing Machinery. https://doi.org/10.1145/3173574.3173610

[51] Jiatong Li, Ryo Suzuki, and Ken Nakagaki. 2023. Physica: Interactive Tangible Physics Simulation based on Tabletop Mobile Robots Towards Explorable Physics Education. In *Proceedings of the 2023 ACM Designing Interactive Systems Conference (DIS '23)*. Association for Computing Machinery. https://doi.org/10.1145/3563657.3596037

[52] Josip Tomo Licardo, Mihael Domjan, and Tihomir Orehovački. 2024. Intelligent Robotics—A Systematic Review of Emerging Technologies and Trends. *Electronics* (2024). https://doi.org/10.3390/electronics13030542

[53] Matteo Luperto, Javier Monroy, Francisco-Angel Moreno, Francesca Lunardini, Jennifer Renoux, Andrej Krpic, Cipriano Galindo, Simona Ferrante, Nicola Basilico, Javier Gonzalez-Jimenez, and N. Alberto Borghese. 2023. Seeking at-home long-term autonomy of assistive mobile robots through the integration with an IoT-based monitoring system. *Robotics and Autonomous Systems* (2023). https://doi.org/10.1016/j.robot.2022.104346

[54] Michal Luria, Guy Hoffman, and Oren Zuckerman. 2017. Comparing Social Robot, Screen and Voice Interfaces for Smart-Home Control. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. Association for Computing Machinery. https://doi.org/10.1145/3025453.3025786

[55] Xiaoning Ma, Xin Yang, Shengdong Zhao, Chi-Wing Fu, Ziquan Lan, and Yiming Pu. 2012. Robots in my contact list: using social media platforms for human-robot interaction in domestic environment. In *Proceedings of the 10th Asia Pacific Conference on Computer Human Interaction (APCHI '12)*. Association for Computing Machinery. https://doi.org/10.1145/2350046.2350076

[56] Kayla Matheus. 2023. Socially Assistive Robotics for Anxiety Reduction. In *Companion of the 2023 ACM/IEEE International Conference on Human-Robot Interaction (HRI '23)*. https://doi.org/10.1145/3568294.3579970

[57] Joseph E. Michaelis and Bilge Mutlu. 2017. Someone to Read with: Design of and Experiences with an In-Home Learning Companion Robot for Reading. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. Association for Computing Machinery. https://doi.org/10.1145/3025453.3025499

[58] M.P. Michalowski, S. Sabanovic, and R. Simmons. 2006. A spatial model of engagement for a social robot. In *9th IEEE international workshop on advanced motion control, 2006*. https://doi.org/10.1109/AMC.2006.1631755

[59] V S Midhun, M Pondurai, and S Vairaprakash. 2024. Floor Cleaning Robot with Android-Based Voice Command. In *2024 International Conference on Wireless Communications Signal Processing and Networking (WiSPNET '24)*. https://doi.org/10.1109/WiSPNET61464.2024.10533035

[60] Sanika Moharana, Alejandro E. Panduro, Hee Rin Lee, and Laurel D. Riek. 2020. Robots for joy, robots for sorrow: community based robot design for dementia caregivers. In *Proceedings of the 14th ACM/IEEE International Conference on Human-Robot Interaction (HRI '19)*. https://doi.org/10.1109/HRI.2019.8673206

[61] Ken Nakagaki, Joanne Leong, Jordan L. Tappa, João Wilbert, and Hiroshi Ishii. 2020. HERMITS: Dynamically Reconfiguring the Interactivity of Self-propelled TUIs with Mechanical Shell Add-ons. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology (UIST '20)*. https://doi.org/10.1145/3379337.3415831

[62] Jauwairia Nasir, Barbara Bruno, and Pierre Dillenbourg. 2024. Social robots as skilled ignorant peers for supporting learning. *Frontiers in Robotics and AI* (2024). https://doi.org/10.3389/frobt.2024.1385780

[63] Yusaku Nishiwaki, Masugi Furukawa, Soshi Yoshikawa, Nihan Karatas, and Michio Okada. 2017. iBones: A Weak Robot to Construct Mutual Coordination for Handing Out Tissue Packs. In *Proceedings of the Companion of the 2017 ACM/IEEE International Conference on Human-Robot Interaction (HRI '17)*. https://doi.org/10.1145/3029798.3036654

[64] Kazutoshi Noda and Hidenobu Aizawa. 2020. Indoor environmental monitoring system using a robot vacuum cleaner. *Sensors and Materials* (2020). https://doi.org/10.18494/SAM.2020.2413

[65] Yuki Onishi, Kazuki Takashima, Shoi Higashiyama, Kazuyuki Fujita, and Yoshifumi Kitamura. 2022. WaddleWalls: Room-scale Interactive Partitioning System using a Swarm of Robotic Partitions. In *Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology (UIST '22)*. https://doi.org/10.1145/3526113.3545615

[66] Linda Onnasch and Eileen Roesler. 2021. A Taxonomy to Structure and Analyze Human–Robot Interaction. *International Journal of Social Robotics* (2021). https://doi.org/10.1007/s12369-020-00666-5

[67] Anastasia K Ostrowski, Cynthia Breazeal, and Hae Won Park. 2021. Research through (co)-Design: engaging older adults in the design of social robots. *Virtual* (2021). https://robots.media.mit.edu/wp-content/uploads/sites/7/2021/04/Ostrowskietal_HRI_2021_RtD_Workshop_Position_Paper_CameraReady.pdf

[68] Xiang Pan, Malcolm Doering, and Takayuki Kanda. 2024. What is your other hand doing, robot? A model of behavior for shopkeeper robot's idle hand. In *Proceedings of the 2024 ACM/IEEE international conference on human-robot interaction (HRI '24)*. https://doi.org/10.1145/3610977.3634986

[69] Caroline Pantofaru, Leila Takayama, Tully Foote, and Bianca Soto. 2012. Exploring the Role of Robots in Home Organization. In *Proceedings of the Seventh Annual ACM/IEEE International Conference on Human-Robot Interaction (HRI '12)*. https://doi.org/10.1145/2157689.2157805

[70] Hannah R. M. Pelikan, Mathias Broth, and Leelo Keevallik. 2020. "Are You Sad, Cozmo?": How Humans Make Sense of a Home Robot's Emotion Displays. In *Proceedings of the 2020 ACM/IEEE International Conference on Human-Robot Interaction (HRI '20)*. https://doi.org/10.1145/3319502.3374814

[71] Shokoofeh Pourmehr, Valiallah (Mani) Monajjemi, Seyed Abbas Sadat, Fei Zhan, Jens Wawerla, Greg Mori, and Richard Vaughan. 2014. "You are green": a touch-to-name interaction in an integrated multi-modal multi-robot HRI system. In *Proceedings of the 2014 ACM/IEEE International Conference on Human-Robot Interaction (HRI '14)*. https://doi.org/10.1145/2559636.2559806

[72] Meiying Qin, Yiyun Huang, Ellen Stumph, Laurie Santos, and Brian Scassellati. 2020. Dog Sit! Domestic Dogs (Canis familiaris) Follow a Robot's Sit Commands. In *Companion of the 2020 ACM/IEEE International Conference on Human-Robot Interaction (HRI '20)*. https://doi.org/10.1145/3371382.3380734

[73] Frederic Anthony Robinson, Oliver Bown, and Mari Velonaki. 2023. Spatially Distributed Robot Sound: A Case Study. In *Proceedings of the 2023 ACM Designing Interactive Systems Conference (DIS '23)*. https://doi.org/10.1145/3563657.3596095

[74] Frederic Anthony Robinson, Mari Velonaki, and Oliver Bown. 2021. Smooth Operator: Tuning Robot Perception Through Artificial Movement Sound. In *Proceedings of the 2021 ACM/IEEE International Conference on Human-Robot Interaction (HRI '21)*. https://doi.org/10.1145/3434073.3444658

[75] Matthew Rueben. 2015. Context-Aware Assistive Interfaces for Persons with Severe Motor Disabilities. In *Proceedings of the Tenth Annual ACM/IEEE International Conference on Human-Robot Interaction Extended Abstracts (HRI'15 Extended Abstracts)*. https://doi.org/10.1145/2701973.2702707

[76] Daisuke Sakamoto, Koichiro Honda, Masahiko Inami, and Takeo Igarashi. 2009. Sketch and run: a stroke-based interface for home robots. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '09)*. Association for Computing Machinery. https://doi.org/10.1145/1518701.1518733

[77] Diana Saplacan and Jo Herstad. 2019. An explorative study on motion as feedback: using semi-autonomous robots in domestic settings. *Int. J. Adv. Softw* (2019). https://personales.upv.es/thinkmind/dl/journals/soft/soft_v12_n12_2019/soft_v12_n12_2019_6.pdf

[78] Paul Saulnier, Ehud Sharlin, and Saul Greenberg. 2009. Using bio-electrical signals to influence the social behaviours of domesticated robots. In *Proceedings of the 4th ACM/IEEE International Conference on Human Robot Interaction (HRI '09)*. https://doi.org/10.1145/1514095.1514167

[79] Eike Schneiders, Anne Marie Kanstrup, Jesper Kjeldskov, and Mikael B. Skov. 2021. Domestic Robots and the Dream of Automation: Understanding Human Interaction and Intervention. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21)*. Association for Computing Machinery. https://doi.org/10.1145/3411764.3445629

[80] J. Scholtz. 2003. Theory and evaluation of human robot interactions. In *36th Annual Hawaii International Conference on System Sciences, 2003. Proceedings of the (HICSS '03)*. https://doi.org/10.1109/HICSS.2003.1174284

[81] Nur Muhammad Mahi Shafiullah, Anant Rai, Haritheja Etukuru, Yiqian Liu, Ishan Misra, Soumith Chintala, and Lerrel Pinto. 2023. On bringing robots home. *arXiv preprint arXiv:2311.16098* (2023). https://doi.org/10.48550/arXiv.2311.16098

[82] Mimo Shirasaka, Tatsuya Matsushima, Soshi Tsunashima, Yuya Ikeda, Aoi Horo, So Ikoma, Chikaha Tsuji, Hikaru Wada, Tsunekazu Omija, Dai Komukai, Yutaka Matsuo, and Yusuke Iwasawa. 2024. Self-Recovery Prompting: Promptable General Purpose Service Robot System with Foundation Models and Self-Recovery. In *2024 IEEE International Conference on Robotics and Automation (ICRA) (ICRA '24)*. https://doi.org/10.1109/ICRA57147.2024.10611640

[83] Majid Shishehgar, Donald Kerr, and Jacqueline Blake. 2018. A systematic review of research into how robotic technology can help older people. *Smart Health* (2018). https://doi.org/10.1016/j.smhl.2018.03.002

[84] Pieter Simoens, Mauro Dragone, and Alessandro Saffiotti. 2018. The Internet of Robotic Things: A review of concept, added value and applications. *International Journal of Advanced Robotic Systems* (2018). https://doi.org/10.1177/1729881418759424

[85] Sichao Song, Jun Baba, Junya Nakanishi, Yuichiro Yoshikawa, and Hiroshi Ishiguro. 2020. Mind The Voice!: Effect of Robot Voice Pitch, Robot Voice Gender, and User Gender on User Perception of Teleoperated Robots. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems (CHI EA '20)*. Association for Computing Machinery. https://doi.org/10.1145/3334480.3382988

[86] Laura Stegner and Bilge Mutlu. 2022. Designing for Caregiving: Integrating Robotic Assistance in Senior Living Communities. In *Proceedings of the 2022 ACM Designing Interactive Systems Conference (DIS '22)*. https://doi.org/10.1145/3532106.3533536

[87] Sophia C. Steinhaeusser and Birgit Lugrin. 2022. Effects of Colored LEDs in Robotic Storytelling on Storytelling Experience and Robot Perception. In *Proceedings of the 2022 ACM/IEEE International Conference on Human-Robot Interaction (HRI '22)*. https://doi.org/10.1109/HRI53351.2022.9889469

[88] Xia Su, Daniel Campos Zamora, and Jon E. Froehlich. 2024. RAIS: Towards A Robotic Mapping and Assessment Tool for Indoor Accessibility Using Commodity Hardware. In *Proceedings of the 26th International ACM SIGACCESS Conference on Computers and Accessibility (ASSETS '24)*. https://doi.org/10.1145/3663548.3688512

[89] Yuta Sugiura, Daisuke Sakamoto, Anusha Withana, Masahiko Inami, and Takeo Igarashi. 2010. Cooking with robots: designing a household system working in open environments. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '10)*. Association for Computing Machinery. https://doi.org/10.1145/1753326.1753693

[90] Sangho Suh, Meng Chen, Bryan Min, Toby Jia-Jun Li, and Haijun Xia. 2024. Luminate: Structured Generation and Exploration of Design Space with Large Language Models for Human-AI Co-Creation. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems (CHI '24)*. Association for Computing Machinery. https://doi.org/10.1145/3613904.3642400

[91] Linghui Sui and Lize Lin. 2020. Design of Household Cleaning Robot Based on Low-cost 2D LIDAR SLAM. In *2020 International Symposium on Autonomous Systems (ISAS '20)*. https://doi.org/10.1109/ISAS49493.2020.9378863

[92] JaYoung Sung, Rebecca E. Grinter, and Henrik I. Christensen. 2009. "Pimp My Roomba": Designing for Personalization. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '09)*. Association for Computing Machinery. https://doi.org/10.1145/1518701.1518732

[93] Ja-Young Sung, Rebecca E. Grinter, Henrik I. Christensen, and Lan Guo. 2008. Housewives or Technophiles? Understanding Domestic Robot Owners. In *Proceedings of the 3rd ACM/IEEE International Conference on Human Robot Interaction (HRI '08)*. https://doi.org/10.1145/1349822.1349840

[94] Ryo Suzuki, Hooman Hedayati, Clement Zheng, James L. Bohn, Daniel Szafir, Ellen Yi-Luen Do, Mark D. Gross, and Daniel Leithinger. 2020. RoomShift: Room-scale Dynamic Haptics for VR with Furniture-moving Swarm Robots. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20)*. Association for Computing Machinery. https://doi.org/10.1145/3313831.3376523

[95] Magnus Söderlund. 2023. What is it like to be idle versus busy for a service machine? *Psychology & Marketing* (2023). https://doi.org/10.1002/mar.21806

[96] Kazuaki Takeuchi, Yoichi Yamazaki, and Kentaro Yoshifuji. 2020. Avatar Work: Telework for Disabled People Unable to Go Outside by Using Avatar Robots. In *Companion of the 2020 ACM/IEEE International Conference on Human-Robot Interaction (HRI '20)*. https://doi.org/10.1145/3371382.3380737

[97] Angelique Taylor, Michele Murakami, Soyon Kim, Ryan Chu, and Laurel D. Riek. 2022. Hospitals of the Future: Designing Interactive Robotic Systems for Resilient Emergency Departments. *Proceedings of the ACM on Human-Computer Interaction* (2022). https://doi.org/10.1145/3555543

[98] Milan Tkáčik, Adam Březina, and Slávka Jadlovská. 2019. Design of a Prototype for a Modular Mobile Robotic Platform. *16th IFAC Conference on Programmable Devices and Embedded Systems PDES 2019* (2019). https://doi.org/10.1016/j.ifacol.2019.12.755

[99] Lachlan Urquhart, Dominic Reedman-Flint, and Natalie Leesakul. 2019. Responsible domestic robotics: exploring ethical implications of robots in the home. *Journal of Information, Communication and Ethics in Society* (2019). https://doi.org/10.1108/JICES-12-2018-0096

[100] David van der Pol, Raymond H. Cuijpers, and James F. Juola. 2011. Head pose estimation for a domestic robot. In *Proceedings of the 6th International Conference on Human-Robot Interaction (HRI '11)*. Association for Computing Machinery. https://doi.org/10.1145/1957656.1957769

[101] Michael L Walters, Kerstin Dautenhahn, René Te Boekhorst, Kheng Lee Koay, Dag Sverre Syrdal, and Chrystopher L Nehaniv. 2009. An empirical framework for human-robot proxemics. In *Procs of new frontiers in human-robot interaction: symposium at the AISB09 convention*. https://uhra.herts.ac.uk/bitstream/handle/2299/9670/903515.pdf

[102] Jimmy Wu, Rika Antonova, Adam Kan, Marion Lepert, Andy Zeng, Shuran Song, Jeannette Bohg, Szymon Rusinkiewicz, and Thomas Funkhouser. 2023. TidyBot: personalized robot assistance with large language models. *Autonomous Robots* (2023). https://doi.org/10.1007/s10514-023-10139-z

[103] Lanyu Xu, Arun Iyengar, and Weisong Shi. 2020. CHA: A Caching Framework for Home-Based Voice Assistant Systems. In *2020 IEEE/ACM Symposium on Edge Computing (SEC)*. https://doi.org/10.1109/SEC50012.2020.00041

[104] Holly A Yanco and Jill L Drury. 2002. A taxonomy for human-robot interaction. In *Proceedings of the AAAI fall symposium on human-robot interaction*. https://cdn.aaai.org/Symposia/Fall/2002/FS-02-03/FS02-03-015.pdf

[105] Pui Yee Leong and Nur Syazreen Ahmad. 2024. Exploring Autonomous Load-Carrying Mobile Robots in Indoor Settings: A Comprehensive Review. *IEEE Access* (2024). https://doi.org/10.1109/ACCESS.2024.3435689

[106] Yan Yixian, Kazuki Takashima, Anthony Tang, Takayuki Tanno, Kazuyuki Fujita, and Yoshifumi Kitamura. 2020. ZoomWalls: Dynamic Walls that Simulate Haptic Infrastructure for Room-scale VR World. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology (UIST '20)*. https://doi.org/10.1145/3379337.3415859

[107] James E. Young, Richard Hawkins, Ehud Sharlin, and Takeo Igarashi. 2009. Toward Acceptable Domestic Robots: Applying Insights from Social Psychology. *International Journal of Social Robotics* (2009). https://doi.org/10.1007/s12369-008-0006-y

[108] Georgios A. Zachiotis, George Andrikopoulos, Randy Gornez, Keisuke Nakamura, and George Nikolakopoulos. 2018. A survey on the application trends of home service robotics. In *2018 IEEE International Conference on Robotics and Biomimetics (ROBIO '18)*. https://doi.org/10.1109/ROBIO.2018.8665127

[109] Fanlong Zeng, Wensheng Gan, Yongheng Wang, Ning Liu, and Philip S Yu. 2023. Large Language Models for Robotics: A Survey. *arXiv preprint arXiv:2311.07226* (2023). https://doi.org/10.48550/arXiv.2311.07226

[110] Brian J. Zhang, Knut Peterson, Christopher A. Sanchez, and Naomi T. Fitter. 2021. Exploring consequential robot sound: Should we make robots quiet and kawaii-et?. In *2021 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS '21)*. https://doi.org/10.1109/IROS51168.2021.9636365

[111] Zhao Zhao and Rhonda McEwen. 2022. "Let's read a book together": A Long-term Study on the Usage of Pre-school Children with Their Home Companion Robot. In *Proceedings of the 2022 ACM/IEEE International Conference on Human-Robot Interaction (HRI '22)*. https://doi.org/10.1109/HRI53351.2022.9889672

[112] John Zimmerman, Jodi Forlizzi, and Shelley Evenson. 2007. Research through Design as a Method for Interaction Design Research in HCI. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '07)*. https://doi.org/10.1145/1240624.1240704