"Space Agency": A "Strong Concept" for Designing Socially Interactive, Robotic Environments

Yixiao Wang[1(✉)] and Keith Evan Green[2]

[1] Research Field: Smart Built Environment and Human Robot Interaction, Singapore University of Technology and Design (SUTD), 8 Somapah Rd, Singapore 487372, Singapore
yixiao_wang@sutd.edu.sg

[2] Research Field: Architectural Robotics, Cornell University, Ithaca, NY 14850, USA
keg95@cornell.edu

Abstract. What if our surrounding built environment could understand our emotions, predict our needs, and otherwise assist us, both physically and socially? What if we could interact with private and public spaces as if these were our friends, partners, and companions — "Space Agents"? "Space Agents" are here defined as robotic, smart built environments designed to be perceived or interacted with as socially intelligent agents. In this paper, we consider Space Agency both as a "Strong Concept" (a category of generative, intermediate-level design knowledge), and as a new research field of "socially interactive smart built environment" for Social Robotics, HAI, and HCI communities. "Space Agency" is considered with respect to previous empirical and theoretical works of HCI and Architecture and also by our own recent work on a socially adaptive wall. We conclude this paper by advancing the generalizability, novelty, and substantivity of "Space Agency" as a Strong Concept, abstracted beyond specific design instances which designers and researchers, in turn, can use to ideate and generate new design instances of social robots.

Keywords: Space agent · Strong concept · Socially interactive smart built environment · Socially intelligent agent · Interaction design theory

1 Introduction

With the rapid development of "industry 4.0," artificial intelligence is being embedded and embodied in our everyday lives more, and more pervasively. As a result, human-machine interactions for conversational agents and social robots are being widely studied, tested, and theorized in HCI communities [1–3]. However, human-machine interactions for Smart Built Environments (SBE) are still underexplored. SBE are "spaces integrated with sensors-actuator systems and intelligent control algorithms" [4]. This paper investigates human-SBE social interactions and relationships through the theoretical lens of generative intermediate-level design knowledge supported by evidence from empirical studies and theoretical works. We argue that "Space Agency" can be a powerful and generative "Strong Concept" through which social human-SBE interactions and relationships can be designed, prototyped, and investigated.

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1.1 Strong Concept as a Category of Intermediate-Level Design Knowledge

Researchers from HCI and HRI have been producing design knowledge in the level of instances and theory predominantly using empirical research methods [5]. However, as designers and design researchers, we know there are many cases both in research and practice where we employ and generate pieces of design knowledges such as Patterns, Design Guidelines, Heuristics, etc. that are more abstract than specific design instances, but less generalizable than a theory. This kind of design knowledge is characterized as intermediate-level design knowledge [5–7]. Intermediate level design knowledge serves as an abstraction or, more specifically, a common annotation of different design instances from one family [5–7]. There are two categories of design knowledge: evaluative and generative knowledge. Evaluative intermediate-level knowledge such as Design Heuristics and Criticism tend to synthesize and evaluate design instances, while generative intermediate-level design knowledge such as Patterns, Guidelines, and Strong Concepts tend to inspire and generate new designs [5]. Strong Concepts are design elements abstracted beyond specific design instances and can be potentially appropriated by designers and researchers to ideate and generate new design instances [5].

1.2 "Space Agency" Towards a Strong Concept

"Space Agency" characterizes SBEs and their spatial elements (e.g., walls, floors, furnishings, etc.) designed to be perceived or interacted with as socially intelligent agents [8, 9]. For instance, the adaptive or interactive behavior of a smart chair, wall, or room, if carefully designed, can be perceived by users as socially expressive – as welcoming, inviting, friendly, etc. "Space Agency" fits the four characteristics of Strong Concept given by Hook and Lowgren [5]:

- It concerns user perception of interactive behaviors of the spatial elements, which will shape the user interactions unfolding over time;
- It resides in the interface between SBE and users, manifesting itself as design elements (e.g., motions, trajectories, etc.) supporting socially expressive interactions.
- It has been a core design idea at the very beginning of the design process and can cut across different use cases of, for instance, a stool, a door, a wall, etc.;
- It resides on an abstract level and can/should be realized in different aspects of a design including interaction patterns, interaction modalities, form factors, etc.

1.3 Key Contributions of "Space Agency" to Social Robotics, HAI, and HCI

The key contributions of "Space Agency" are:

A New Generative Intermediate-Level Design Knowledge. This paper proposes and validates the design knowledge of "Space Agency," which is a substantive Strong Concept with generative power. Through "Space Agency," we can design and generate interactive and adaptive SBE, perceived as our friends, companions, partners, playmates, etc.

Socially Interactive SBEs as a New Research Field for Human-Building Interaction. Human-Building Interaction (HBI) [10] is a nascent research field in interaction design community. In HBI, there is no established design knowledge informing the design researchers that buildings can be designed, perceived, and investigated as socially intelligent agents (as will be demonstrated in Sect. 3). Just as in HCI, software interfaces can be designed as embodied conversational agents that are intelligent and social [1], so in HRI, robots can be designed as socially intelligent and interactive [2]. Following this trajectory, we now argue that in HBI, buildings can also be designed and perceived as socially intelligent and interactive, which is the essence of "Space Agency."

2 Methodology

A key aim of this paper is to characterize "Space Agency" as a Strong Concept that is academically contestable, defensible, and substantive so that design researchers could confidently employ this concept in their design works, investigate this concept through empirical studies, and build upon this concept in theoretical discussions [11, 12]. Thus, we follow the Strong Concept construction process elaborated by Hook and Lowgren as an "exercise in epistemology" [5]:

- For the source of this Strong Concept, we present our design instance of the "socially adaptive robotic wall" in Sect. 4 and illustrate how "Space Agency" is applied to and evaluated in this design instance;
- For the horizontal grounding of this Strong Concept, we review the most relevant empirical works in "Human Building Interaction" (HBI) and "Large-scale Shape-changing Interface" in Sect. 3;
- For the vertical grounding of this Strong Concept, we investigate the theoretical works from both Architecture and HCI and illustrate how the embodiment of "Socially Intelligent Agent" evolved in the last 20 years in Sect. 3;
- Finally, the nature of this research is presented in Sect. 5 where the generalizability, novelty, and substantivity of "Space Agency" are discussed.

3 Related Works

Our literature review unfolds through the following topics serving as the "horizontal grounding" and "vertical grounding" [5] of "Space Agency" in the intellectual landscape of HCI and HRI design research: "Human-Building Interaction" and "Large-scale Shape-changing Interface" serve as the "horizontal grounding" speaking to the empirical works most closely related to "Space Agency"; "The Theoretical Foundation of 'Space Agency'" serves as the "vertical grounding" speaking to the Architecture and HCI theoretical works that support this Strong Concept.

3.1 Human Building Interaction and Large-Scale Shape-Changing Interface

Human Building Interaction (HBI) is a nascent research field unifying HCI with built environment. HBI focuses on the human perspectives (e.g., values, needs, wants, experiences, etc.) to address people's interaction with interactive or smart built environments [10]. Before HBI was formally introduced to the HCI community [10], designers and researchers from architecture and robotics have been actively exploring human-architecture interaction through empirical works. "Architectural Robotics" [13] investigated user interaction with robotic furnishings [14], a robotic canopy [15], and room-scaled robotic spaces [16].

More recently, HBI researchers investigated user perception of user-controlled virtual walls [17] and user interaction with a dynamic tent-like structure [18]. Grönvall et al. and Suzuki have developed shape-changing interfaces, from furniture-scale to room-scale, whose user interactions were investigated. Grönvall et al. developed a shape-changing bench whose ability to cause "commotions" were explored with hundreds of participants in the wild [19]; Suzuki et al. developed a shape-changing floor with robotic textiles whose formal user evaluation is planned in future work [20].

Although these works widely cover the topics of interactive, responsive, and adaptive built environments, the social expressiveness of SBE has rarely been investigated. Empirical works investigating users' social interaction with SBE majorly focus on the cases of robotic furnishings and spatial envelopes [21–23]. In Sect. 5, we will further discuss how these works cover a wide range of applications in different contexts where social expressiveness of SBE is investigated.

3.2 The Theoretical Foundation of "Space Agency"

In this section, we will define the concept of "socially intelligent agent," discuss the theoretical support for designing a socially interactive SBE, and briefly review the evolving embodiment of socially intelligent agents in HCI history.

How is "Socially Intelligent Agent" Defined? "Socially intelligent agent" refers to an artificial, social actor that is accepted by users through his/her intentional stance based on Dennett's Intentional Stance [24], "whether users are conscious or unconscious of the fact" [25]. For the "social" aspect in this definition, "Socially Intelligent Agent" may show "human-style intelligence" [26], "pet-style intelligence," and even a "hybrid-style intelligence" that are social, yet different from intelligence we can find in nature.

Why Do We Want Our Built Environment to Be Socially Interactive? The answer to this question points to "the common, underlying assumption" that "humans prefer to interact with machines in the same way that they interact with other people" [2]. In the HCI community, this common, underlying assumption has been applied to and validated through countless software and hardware interfaces, such as embodied conversational agents [1] and socially interactive robots [2]. At the same time, in architecture theory, architecture (a building) has long been conceptualized as "a machine for living in" [27], "an environmental, social and cultural device" [28], and more recently, "a robot for living in" [29]. Thus, at the intersection of theoretical works from HCI and Architecture is the argument that "humans may also prefer to interact with "machines for living in" (which are buildings) in the same way that they interact with other people."

The Evolving Embodiment of Socially Intelligent Agent. In the last 20 years, we can see a clear trajectory where the embodiment of a socially intelligent agent has been evolving from virtual to physical, from human figure to shape-changing interface, and from object to space. In 2001, Justine Cassell defined what an "Embodied Conversational Agent" was [1] and convincingly argued why intelligent computer systems should be characterized as human-like in those cases "where social collaborative behavior is the key." The example given by Cassell was a virtual human agent named REA who could "welcome" a user into a virtual office. Arguably, the embodiment of socially intelligent agent does not have to be virtual. Many researchers design anthropomorphic or zoomorphic robots to make human-robot interaction human-like or at least, creature-like [2]. In the past 10 years, there has been growing research interest in socially interactive, nonhumanoid robots. Researchers in this area make robotic lamps, robotic music players, robotic furnishings, etc. that can convey social cues such as sympathy, welcome, politeness, etc. through meticulously designed movements and motions [22, 23, 30]. Most of these nonhumanoid robots are only objects; however, some of them are important spatial elements of built environments, such as doors and furnishings [22, 23].

HRI researchers have also explored how shape-changing interfaces can be perceived as a socially intelligent agent. Hemmert et al. and Pedersen et al. investigated how the surface reconfiguration and movement of a robotic cellphone can be perceived as animal-like [31, 32]. Our own recent work, the development and evaluation of an interior-scale adaptive wall, investigated its perceived social expressiveness including welcome, friendliness, collaboration, and cooperation [33].

By continuing this trajectory, we can see that spaces and their spatial components may be designed and perceived as socially intelligent "Space Agents."

4 Design Instance: An Adaptive Robotic Wall

The authors have developed and evaluated an adaptive robotic wall [33] which can be reconfigured from a vertical wall into a writing surface (Fig. 1). This large-scale, shape-changing interface consists of a 2-inch-thick foam panel and a tendon-driven actuation system with motors, laser-cut wood collars, and 3D-printed brackets (Fig. 1). It can be reconfigured into five different configurations as reported in our previous work [34]. The major applications of this technology are reconfiguring interior spaces (e.g., office, living room, space capsule, etc.) supporting, in our investigation, working life.

4.1 Employing "Space Agency" in the Human-Wall Interaction Design

When designing the human-robot interaction of our robotic wall, we wanted its movements to be socially expressive by showing friendliness, welcome, cooperativeness, and collaboration to users. Thus, we designed a scenario where users could freely interact with the robotic wall which was trying to facilitate a simple task through socially

Fig. 1. Our robotic wall (right) prototype and photo from a pilot study with a user (left).

expressive ways. In this scenario, we gave the user a piece of printing paper and asked him/her to copy a short paragraph on a piece of paper in a room, unfurnished, with the robotic wall element flush with a wall surface. In our study, some participants initially began looking for a writing surface to work on but there was none offered by the room; that is, until the robotic wall offered one by bending itself downward with pauses and a gentle speed. By taking the initiative of offering a writing surface, the robotic wall was offering its help in a “welcoming” manner to the participant [23]. By making pauses and bending downward at a gentle speed, it was suggesting “politeness” and “friendliness” [22]. Some participants inspected it further to evaluate its affordances. If the participant moves closer, the robotic wall adjusted its position subtly as a cue, and gently rested itself on the participant’s lap as a writing surface; if the participant selected not to move closer, the robotic wall swung gently up and down to show its willingness to help. This series of movements was a show of “friendliness” and “collaboration” to the user [30]. After the copying task was finished, the robotic wall automatically returned to its original position, flush with the wall surface.

The experiment scenario and robotic wall movement were designed by five HRI researchers through iterations and informed by the literature of designing socially interactive, nonhumanoid robots [22, 23, 30].

4.2 In-Lab and Online Experiment Design

Based on this scenario, we conducted an in-lab, between-group experiment with ten college students (ages 19–34, 7 FM, 3 M) and one mature adult (59, FM). The 5 participants in the treatment group went through the scenario in which the adaptive wall behavior was simulated using WoZ techniques [35] where an experimenter controlled (teleoperated) the robotic wall movement behind the one-way window. The 5 participants in the control group were given the remote controller for the wall their usage before starting the copying task. Both the treatment group [36] and control group [37], the trials were video recorded. After finishing the task, participants answered the same questionnaire probing users' social perception, whose questions were modified from a validated scale of "Social Perception." "Social Perception" scale measures four subconstructs: friendliness, cooperativeness, sociability, and warmth [38]. Our modified questionnaire measures seven subconstructs: friendliness, cooperativeness, collaboration, welcome, intelligence, recognition, and intention. In our modified questionnaire, we replaced "warmth" with "welcome," "sociability" with "collaboration" so that it's more context-specific for our experiment scenario – a human-robot collaborative task for a novice user. We also added "intelligence," "recognition," and "intention" to our questionnaire based on the measurements from robotic furnishing literature [22, 23]. At the end of the questionnaire, three open-ended questions were asked to probe the reasons for agency perception.

To compensate for the lack of in-lab participants (given the closure of our lab due to the pandemic), an online, between-group study was conducted with 120 MTurk Master Workers "proven reliable" in previous studies, 60 assigned to each group: treatment and control (41 FM, 79 M; 65 workers 25–39; 52 workers 40–60; 2 workers over 60; 1 worker 18–24). Workers were paid a high market rate of 1.5 and 1.2 dollars respectively for participating in the 15-min (treatment group) or 12-min (control group). The intervention for treatment group participants was the "treatment group video" [36], while for control group participants was the "control group video" [37]. After watching the video, the participants answered the same questionnaire used in the in-lab experiment.

4.3 Results and Findings

Figure 2 shows the descriptive statistics of the seven subconstructs. The coding for each subconstruct in Fig. 2 is: "Intel" for Perceived Intelligence, "Rec" for Perceived Recognition, "Inten" for Perceived Intention, "Coop" for Perceived Cooperation, "Col" for Perceived Collaboration, "Fri" for Perceived Friendliness, and "Wel" for Perceived Welcome. The median values from the treatment group are all equal to or greater than 5 (somewhat agree); while values from the control group range from 2 (disagree) to 4 (neutral). The differences between Md (treatment group) and Md (control group) for these seven subconstructs range from 1.75 to 3.00. This suggests that participants in the treatment group perceived significantly more intelligence, recognition, intention, cooperativeness, collaboration, friendliness, and welcome from the robotic wall. We then ran a Kruskal-Wallis H test which also indicates there is a statistically significant difference ($p < 0.001$) in users' social perception of all the seven subconstructs between the treatment group and control group.

The qualitative results unveiled the reasons for users' agency perception: the users believed that the robotic wall recognized the situation (a writing surface was needed) and then performed an intentional and helpful act (providing a writing surface). The full detailed results of the study were reported in [33].

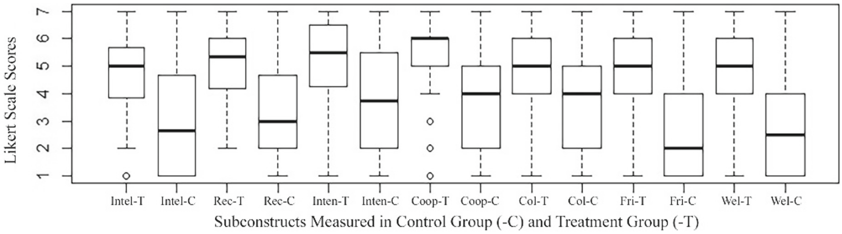

Fig. 2. Descriptive statistics of the seven subconstructs.

5 Discussion: Generalizability, Novelty, and Substantivity

With respect to the generalizability of this Strong Concept, "Space Agency" has characterized various SBE design research artifacts, ranging from smart furnishings to smart, spatial envelops in a variety of situations. Examples of design instances include a smart ottoman in an interior waiting room encouraging users to rest their feet on it [22], a smart chair in the public space of a shopping mall inviting shoppers to play chess [21], a smart door welcoming pedestrian from the street to come into a building [23], a smart sofa

Table 1. Comparison of previous works employing "space agency."

Project	Category	Experiment condition	Function	Users' social perception
Mechanical Ottoman [22]	Furniture	In-lab Study	Actively providing a footrest	It has sentience, intention, and personality; it's alive, like a pet
Persuasive ChairBots [21]	Furniture	Field Study	Actively persuading pedestrians to play chess	It's inviting, submissive, friendly; For some people, it's creepy
Sofa-Bot [39]	Furniture	In-lab Study	Moving according to users' movements and gestures	It has sentience, intention, and personality; It's building a relationship with users
Robotic Drawers [40]	Furniture	In-lab Study	Collaborating with users for an assembly task	It's socially expressive, proactive, and intentional. It's like a boss sometimes

(*continued*)

Table 1. (*continued*)

Project	Category	Experiment condition	Function	Users' social perception
Gesturing Doors [23]	Furniture (Part of a Spatial Envelop)	Field Study	Inviting users into a building	It's welcoming, urging, and sometimes reluctant. It's approachable, intentional, and recognizant
Adaptive Robotic Wall [33]	Spatial Envelop	In-lab Study	Collaborating with users to perform a writing task	It's intentional, recognizant, friendly, welcoming, cooperative, and collaborative

that follows users' gestures to reposition itself in a multifunctional large space [39], a robotic drawer that collaborates with users to perform assembly tasks [40], and our work s reported here, in brief, of the adaptive wall collaborating with participants engaged in a writing task in an interior workspace [33]. Table 1 compares these projects with each other through their categories, experiment conditions, functions, and users' social perceptions as a validation for the generalizability of "Space Agency." Table 1 may not be an exhaustive list of previous works employing "Space Agency."

From Table 1, we see that the "Adaptive Robotic Wall" extended the previous works of socially interactive, robotic furnishings to socially interactive, spatial envelops. Like robotic furnishings, people perceive social expressiveness (intention, recognition, friendliness, welcome, cooperativeness, and collaboration) from the robotic wall.

With respect to the novelty of "Space Agency," this paper argues for the first time, to our knowledge, that an SBE can be contestably, defensibly, and substantively conceptualized as an embodiment in social robotics [3]. "Space Agency" also represents a new category of design knowledge whose concept has never been rigorously discussed and justified as a design theory contribution. Moreover, "Space Agency" introduces an opportune marriage between environmental psychology and social robotics, since a socially interactive SBE influence people's mental state not only through social interactions but also the environment people living in.

With respect to the substantivity of this Strong Concept, we illustrated how "Space Agency" was applied in our robotic wall, interaction design process. The generative power of "Space Agency" has also been proved by the interaction design process of robotic furnishings [21–23] where "Embodied Design Improvisation" [30] was employed as a design method to create the socially expressive robot movement.

6 Limitation

There are several limitations to this work:

- As shown in Table 1, most of the previous works employing "Space Agency" in the design process are robotic furnishings. More works of different kinds of robotic, environmental elements (e.g., robotic walls, ceilings, etc.) are needed for a better understanding of "Space Agency" in different embodiments.
- For the "Adaptive Robotic Wall" experiment, personality, sex, age, and technology literacy of each participant could be effective factors. Further investigations on these factors are necessary for a better understanding of users' agency perception.
- All the previous works employing "Space Agency" focused on the investigation of robot movements, physical embodiment, and interaction modes. The spatial and environmental attributes of socially interactive, robotic environments were rarely investigated. These attributes need to be explored before "Space Agency" can be better understood and developed in design theories and real-world applications.

7 Conclusion and Future Work

In this paper, we proposed and validated the intermediate-level design knowledge of "Space Agency" through the triangulation of empirical, analytical, and theoretical domains. As a Strong Concept, "Space Agency" offers designers and researchers a grounding from which to ideate and generate new design instances of social robots. Through "Space Agency," we know that SBE and its spatial elements can be designed and perceived as socially interactive. Our next questions might be: *How can socially interactive SBE be socially assistive? What are the cases "where social collaborative behavior is the key" in human-SBE interaction? What kind of social relationships should we create between human and an SBE?* Moreover, we could explore how an SBE might exhibit the following social characteristics inspired by [2]:

- expresses and/or perceives emotions;
- constitutes a conversational agent with spatial embodiment conveying social cues;
- constitutes a social agent that is competent and assistive in different contexts;
- establishes/maintains multimodal social interactions;
- establishes/maintains social relationships;
- exhibits distinctive personality and character;
- employs spatial/environmental embodiment for human-SBE collaboration.

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