# Designing Socially Interactive, Robotic Environments through Pattern Languages

2022 18th International Conference on Intelligent Environments (IE) | 978-1-6654-6934-0/22/$31.00 ©2022 IEEE | DOI: 10.1109/IE54923.2022.9826761

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***Abstract*— Architecture has long been conceptualized as "a machine for living in" and more recently as "a robot for living in." Human-Robot Interaction (HRI) has developed robots as social agents—our friends, companions, and partners. Could robotic environments be perceived and interacted with as socially intelligent agents? If so, how should we design a Socially Interactive, Robotic Environment (SIRE)? To address the first question, we offer the empirical evidence and theoretical support of SIREs. We then address the second question by discussing the "Spatial Design" and "Interaction Design" of SIREs through an explorative, pattern-based approach. For "Spatial Design," we present a co-design study for a partner-like office, generating new spatial patterns that form pattern languages to convey sociality to individual users. For "Interaction Design," we employed four "Design Patterns for Sociality in HRI." Our results show that "Spatial Patterns" and "HRI Patterns" can be integrated as one pattern language for sociality and that such a pattern language can vary from person to person. Through the explorative works of this paper, we wish to introduce SIRE to IE communities and cultivate the conversation about the design and application of SIREs in everyday life.**

***Keywords*— *Socially Interactive Robotic Environment (SIRE), design patterns, partner-like office, Intelligent Environment (IE)***

## I. Introduction

"Robotic environments" are spaces embedded with robotic components that make physical environments reconfigurable. Since the early 2000s, design researchers and architects around the world began developing interactive and adaptive spatial components such as robotic walls, ceilings, partitions, and furnishings. Pioneers in this area affiliated with the MIT Media Lab [1], TU Delft's Hyperbody Research Group [2], the Architectural Association Design Research Lab [3], and Cornell University's Architectural Robotics Lab [4], among others. Due to the fast development of robotics technologies and extensive research efforts from communities such as IE [5] and HBI (Human-Building Interaction) [6], robotic environments are becoming more and more pervasive and technically mature. Meanwhile, in the Human-Robot Interaction (HRI), robots (humanoid and nonhumanoid) have been widely investigated as socially intelligent agents such as our friends, partners, and companions (e.g., [7]). If robots are commonly "humanized" in user perception and interaction, could robotic environments also be "humanized"?

Philosophically, "humanizing" environments is not a new idea. Since the 1970s, sci-fi writers such as James G. Ballard were already writing novels about emotional houses [8]. In academia, visionaries like Negroponte (1970s) were also depicting a partner-like work environment [9]. However, there have been few empirical studies investigating the social perceptions of or interactions with robotic environments, and thus, few theoretical works justifying Socially Interactive Robotic Environments (SIREs) as a contestable, defensible, and substantive piece of design knowledge with generative power [10]. Thus, in the past few years, we have been investigating:

- Can robotic environments be perceived and interacted with as socially intelligent agents?
- If so, how should we design the physical embodiment, robotic movement, and spatial reconfiguration of such SIREs for conveying sociality?

For the first question, in our previous works, we conducted the human-centered design, engineering, and evaluation of a socially interactive robotic wall-table and validated it through in-lab experiments that suggest users perceive our robotic wall-table as a socially intelligent agent [11]. We also did a literature review of existing robotic furnishing projects (e.g., robotic ottoman, chair, drawer, sofa, and door) that were validated empirically as socially interactive or adaptive [12]. The social robotics projects above cover a wide range of spatial components, from furnishings to doors to spatial envelopes. In addition, we also cross-referenced theories from Architecture [13], Interaction Design [7], and Psychology [14] and arrived at the conclusion that "Robotic environments are socially intelligent agents for living in" [12]. Thus, we concluded that robotic environments could be perceived and interacted with as socially intelligent agents [12].

In this paper, in the literature review, we situate our discussion of SIREs in the context of IEs and briefly consider the empirical evidence and theoretical support (mentioned above) as the foundation for further discussion. For the second question, we consider the design of SIREs in two interrelated dimensions: "Spatial Design" (Section V) and "Interaction Design" (Section IV). For "Spatial Design," we report on a co-design study of a partner-like micro-office that was designed to be helpful, welcoming, friendly, and collaborative. Informed by the study results and based on the classical architecture design theory of "*A Pattern Language*" [15], we then characterize our own spatial patterns. These spatial patterns form "spatial pattern languages" for individual users. For the "Interaction Design" within each spatial pattern, we find four "Design Patterns for Sociality in HRI" (HRI patterns) [16]. By integrating our "spatial pattern languages" and HRI patterns, we create pattern languages conveying sociality to individual users through both spatial reconfigurations and interactions. Finally, we discuss the explorative nature of this research, the focus of our design

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discussion, and the "marriage" between spatial and HRI patterns. More broadly, this paper aims to introduce SIRE to the Intelligent Environments (IE) community and start the conversation about the design and application of SIREs in our everyday life.

## II. Literature Review

In this section, we consider the following three bodies of literature:

1) *"'IE' VS 'SIRE'"* situates our discussion of SIRE design in the context of IEs

2) *"Spatial Components in Social Robotics"* serves as empirical evidence supporting that robotic environments can be socially interactive.

3) *"Socially Intelligent Agents for Living In"* provides an interdisciplinary, theoretical lens through which we see robotic environments as socially intelligent agents for living in.

### *A. "IE" VS "SIRE"*

IE aims at "creating systems which integrate a smart environment with ambient intelligence and is based in the pervasive/ubiquitous availability of services" [5]. There are significant overlaps between IE and SIRE:

- They both have sensors, actuators, and ambient intelligence embedded in physical environments [5].
- They both employ AI systems that are recognizant, intentional, helpful, and situation-aware [5, 17].
- They both have autonomous or semi-autonomous behavior enabled by voice control, gesture recognition, and other smart interaction technologies [5, 18].
- They both can shape the ambient environment such as light, sound, and temperature for users [18].
- They both aim to enable human-centric, easy, natural, unencumbered, privacy-respecting, and safe human-environment interactions [5, 18, 19].

Nevertheless, IE and SIRE have different focuses:

*SIRE strives to create social relationships between inhabitants and environments* [12]. SIRE inherits this focus from HRI [7]. SIREs could become an intimate partner of users by being proactively assistive (which is also emphasized by IE [5, 18]), however, SIRE could also be socially expressive (e.g., being shy, curious, or caring) and play other social roles (e.g., being a friend, a pet, or a companion) in human-environment interaction [7, 12].

*SIRE focuses on the physical embodiment, robotic movement, and spatial reconfigurations of the environment* enabled by the embedded robotic components [12]. SIRE inherits this focus from HRI [7] and Architectural Robotics [20] to investigate how these features could shape inhabitants' activity, behavior, perception, mentality, etc. IE, however, usually does not reconfigure the shape or position of spatial components and thus, does not enable robotic movement or spatial reconfigurations.

### *B. Spatial Components in Social Robotics*

In social robotics and HRI communities, design researchers have developed socially interactive spatial components ranging from smart furnishings to smart, spatial envelops and investigated the user perceptions and interactions through empirical studies. Examples include a mechanical ottoman that encourages users to rest their feet on it in a waiting room [21], a mobile chair that invites shoppers to sit down and play chess in a shopping center [22], a robotic door that invites pedestrians from the street to come into a building [23], a smart sofa that follows user's guide to reposition itself in a capacious interior space [24], a robotic drawer that collaborates with users to perform assembly tasks [25], and our work of a wall-table that collaborates with participants to engage them in a writing task in a private office [11]. Table I compares these projects with each other through their categories, functions, and users' social perceptions. Since all these projects have empirical studies evaluating users' social perception, they empirically support that robotic environments could be perceived and interacted with as socially intelligent agents.

TABLE I. Previous Works of Robotic Spatial Components That Are Socially Interactive

| Project | Function | Users' Social Perception |
|---|---|---|
| Mechanical Ottoman [21] | Providing a footrest | It is sentential and intentional; it seems to be a pet with personalities. |
| Persuasive Chairbot [22] | Persuading people to sit down and play chess | In general, people see it as inviting, submissive, and friendly. However, some people find it creepy. |
| Sofa-Bot [24] | Following user's gestural guidance to move around | It is sentential and intentional; It has a personality and builds relationships with the user. |
| Robotic Drawers [25] | Collaborating with the user to do an assembly task | It is socially expressive, intentional, proactive, and sometimes bossy; Social interaction reduced the perceived domination. |
| Gesturing Doors [23] | Inviting pedestrians to come into a building | It is welcoming, urging, and sometimes reluctant. It is approachable, intentional, and recognizant. |
| Adaptive Robotic Wall [11] | Assisting the user to perform a writing task | It's intelligent, intentional, recognizant, friendly, welcoming, cooperative, and collaborative. |

[a] This is NOT an exhaustive project list of empirically validated SIREs.

### *C. Socially Intelligent Agents for Living In*

Why do we want robotic environments to be socially interactive? In HRI and HCI, 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" [7, 26]. In psychology, this assumption can be traced back to "Anthropomorphism" which describes the psychological mechanisms that people use self-related or anthropocentric knowledge structures to make sense of and interact with nonhuman things [14]. The "nonhuman things" here include humanoid [7], nonhumanoid [7], and potentially robotic environments since people have been anthropomorphizing environments (e.g., "mother earth" and "the spirit of forests") long before robots appear [27, 28]. At the same time, in architecture theory, architecture (a building) has long been conceptualized as "a machine for living in" [29], and more recently, "a robot for living in" [13]. At the intersection of Interaction Design, Psychology, and Architecture theories is the argument that "humans may also prefer to interact with 'robots for living in' (which are robotic environments) in the same way that they interact with other people." Thus, theoretically, robotic environments could be socially intelligent agents for living in.

## III. METHODOLOGY: PATTERNS

How should we design SIREs? There are no right or wrong answers to this question, however, there are good or bad designs. SIRE is like a coin with two sides: one side is "a space that is physically reconfigurable" and the other is "a robot that is socially interactive." Thus, one way to approach SIRE design, we argue, is to take this space-robot duality into consideration and employ a strategy that can sufficiently and coherently address both the spatial and interaction designs. The strategy we identified is "Pattern."

First, "Pattern" could be "Spatial Pattern" in the classical architecture design theory of "A Pattern Language" [15] where different spatial configurations (or "patterns"), which were abstracted from our everyday life, were corresponded with human activities. Below is an example of such a pattern: a spatial configuration that supports people sitting in a circle:

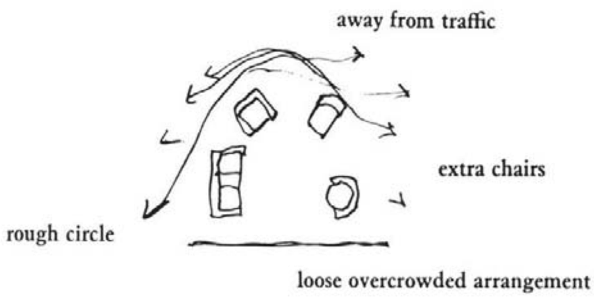



Fig. 1. Pattern number 185, "Sitting Circle" [15]

When patterns like this come together, they become a language that is shared by a group of people. In the book, Alexander et al. strongly encouraged readers to create their own "patterns" and "pattern languages" which exist in every individual's own mind [15]. Thus, for the "Spatial Design" exploration of SIREs, we decided to harvest the "Spatial Patterns" in users' minds through a co-design approach so that we could create our own patterns and pattern languages.

In addition, "A Pattern Language" has been widely appropriated to HCI [30] and HRI [16] designs where the "Pattern" refers to "Interaction Pattern" instead of "Spatial Pattern." Thus, for the interaction design of SIREs, we could employ some of the eight "Design Patterns for Sociality in HRI" ("HRI Patterns" for short) [16] to guide our design process.

Arguably, "Pattern" has become a bridge that originated from "Spatial Design" and landed in "Interaction Design," and SIREs have become the perfect testbed to unite "Spatial Patterns" and "HRI Patterns" into one pattern language that conveys sociality.

## IV. SCENARIO

"Scenario" has been widely used to explore and help define what a new piece of technology should be in real life. For instance, it has been used to depict "how AI could participate in real-world activities" for the creation of early IEs in the 1990s [16]. Thus, we employed the same technique to explore what a SIRE could be in real life. The italic texts below describe how designer Joanne (our persona) works together with a partner-like micro-office throughout the day. The walls and ceiling of the micro-office are embedded with robot surfaces [31] which can be reconfigured into different shapes in different positions to support work activities. This technology was envisioned to make the most out of confined spaces that are extremely valuable and pricy (e.g., in cities like New York, Tokyo, and Hongkong) or need to support different activities within one space (e.g., space capsules, RVs, and submarines).

*In the morning, Joanne and her client come into the office. The office welcomes them by reconfiguring the space to Joanne's default working environment. They sit down together and discuss a project. During the discussion, Joanne wants to take some notes. The situation-aware AI identifies her needs and autonomously provides a tablet for notetaking through a robot surface* (Task1: Note Taking).

*They are in a discussion. Suddenly, Joanne receives an urgent email requiring her immediate attention. She needs privacy to answer the email, so she wants a private space. The AI identifies her need and the robot surfaces divide space into two parts for Joanne's and her client's private working* (Task2: Private Working).

Fig. 2. One possible spatial configuration for Task2: Private Working.

*Joanne wants to present some of her design ideas and sketches to clients. So, she would like the robot surfaces with bendable screens to provide a big presentation screen at the right position. She voice-commanded the office to turn into presentation mode* (Task3: Presentation).

*After a long day of work, clients have left. Joanne feels tired. The AI identifies her emotion and situation, and automatically provides a soft robot surface supporting her back with an ergonomic and comfortable curvature* (Task4: Body Support).

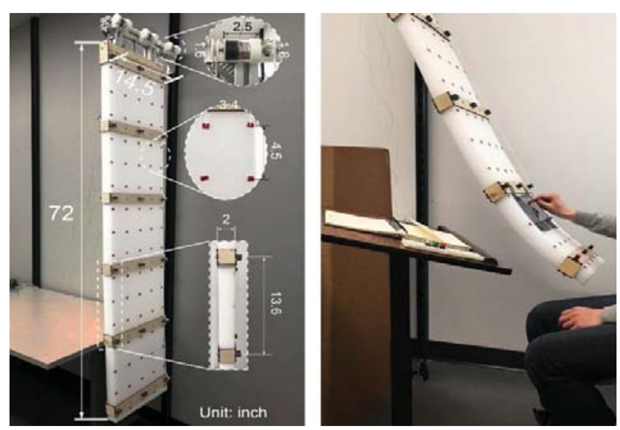



Fig. 3. A full-scale robot-surface prototype providing a tablet.

Fig. 2 shows what robot surfaces might look like and how they could support "Task2: Private Working" as an example. Fig. 3 shows we have developed a robot surface prototype [31] capable of reconfiguring space and providing tablets/screens. However, this prototype is not strong enough to support body weight. In this paper, we will not elaborate on the robot surface mechanism since it's not our focus here.

## V. Identifying Spatial Patterns through Co-Design

To identify the spatial patterns in users' minds [15] regarding this new piece of technology, we conducted a co-design study with 12 participants who were all university students with a design major (interior design, fashion design, and UX design; 5 undergraduates, 7 graduates; ages 18-32; 4 FM, 8 M). They were recruited through posters and convenient sampling. This study was conducted in a controlled lab environment (as shown in Fig.4).

### A. Study Design

This is an exploratory, qualitative user study that took about 40 minutes for each participant who was compensated with a 10-USD amazon gift card. During the co-design process, participants' design was recorded through notes, pictures, and short videos (for the robot surface's trajectories in motion). Below are step-by-step descriptions of the study process:

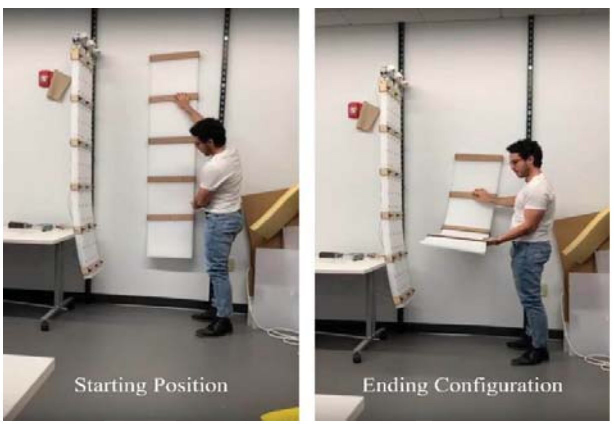



Fig. 4. Co-design for Task1: Note Taking.

First, the participant was invited into the lab in which an experimenter introduced the robot surface technology through physical prototypes (see Fig. 3) and video demonstrations [32]. This introduction not only makes the participant familiar with the robot surface technology, but also gives the participant a better understanding of the robot surface's reconfiguration capabilities (e.g., soft bend, strong bend, angled, and twist.).

Next, the scenario was introduced to the participant through pictures (e.g., Fig. 2 describes Task2: Presentation) and verbal descriptions. These pictures were not suggesting how people should interact with this technology. They only served as an introduction to give the participant a better understanding of the scenario and robot surface technology so that they do not feel confused.

Then, the participant interacted with the full-scale prototype to experience how the robot surface could be autonomously assistive for the "Note Taking" task (see Fig. 3). The autonomous interaction was simulated through WoZ [33] technique by experimenters.

Finally, for each task in the scenario, the participant co-designed with experimenters the starting position, moving trajectory, and ending configuration of the robot surfaces within a compact space (see Fig. 4). This information was captured through short videos and photos which serve as the raw material for generating spatial patterns for each task.

### B. Results

We included 92% of the robot surface configurations designed by the 12 participants in Table II. The very few configurations not included were either not applicable (e.g., the robot surface designed in a position where the embedded screen could be stepped upon.) or not useful. The name of each row refers to different tasks (e.g., "T1" for "Task1," "T2" for "Task2," etc.) and the name of each column refers to the starting position of the robot surface before the reconfiguration begins. At the bottom of each configuration are the tags of participants who designed that configuration. We use "P1" as short for "Participant 1," "P2" for "Participant 2," "P3" for "Participant 3," etc. The "Starting Position," "Ending Configuration," and "Surface Motion Trajectories" are presented and color-coded in the pictures.

Informed by Table II, we see that the starting positions could be ceiling-embedded, perpendicularly wall-embedded, horizontally wall-embedded, or furniture-embedded. Each picture (or diagram) in Table II is a new spatial pattern generated by the users.

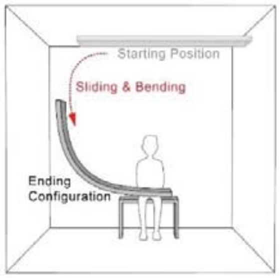
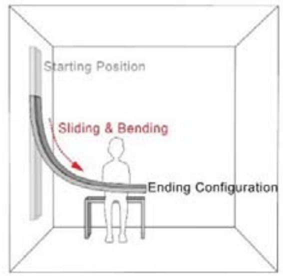
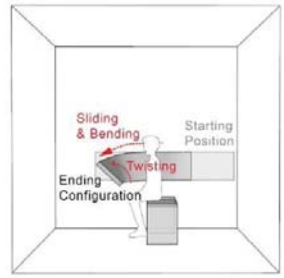
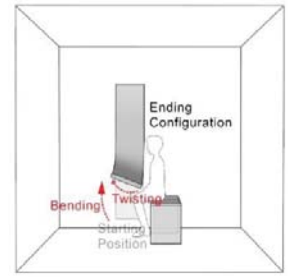
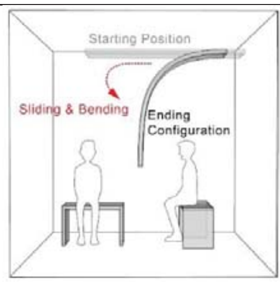
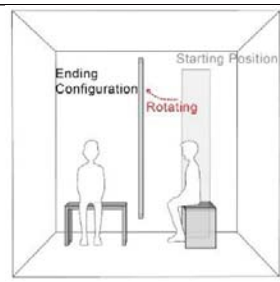
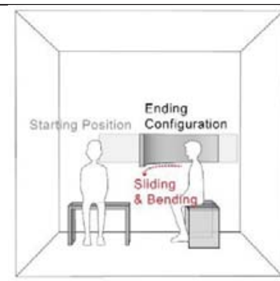
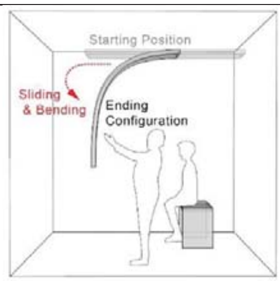
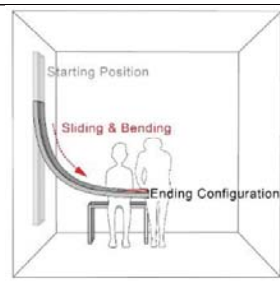
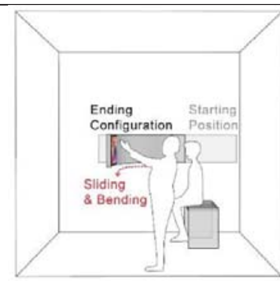
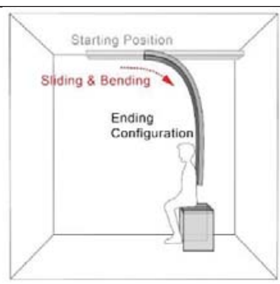
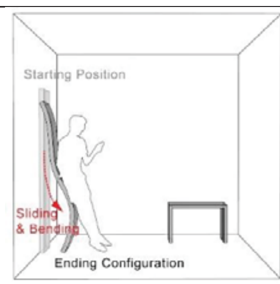
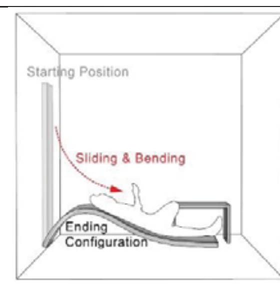
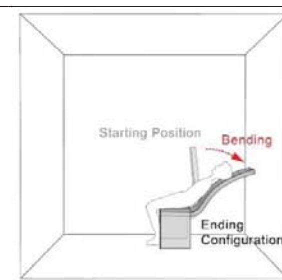
A closer examination of Table II reveals how "spatial pattern languages" emerged through this co-design process. For the convenience of further analysis, we will use the row and column numbers of Table II to refer to a specific pattern. For instance, "T1-2" refers to the pattern in row 1, column 2; "T3-1" refers to the pattern in row 3, column 1, etc.

We can see that some spatial patterns are very commonly shared by users (e.g., T1-2, T1-3, and T2-1) while others are not very popular. We listed four participants and their designed patterns below as examples for further discussions:

- P2 designed T1-3, T2-3, T3-2, and T4-1;
- P5 designed T1-2, T2-1, T3-1, and T4-2;
- P8 designed T1-2, T2-1, T3-1, and T4-2;
- P9 designed T1-2, T2-2, T3-1, and T4-3.

For some participants, such as P5 and P8, they share the exact same spatial pattern language; Most participants, such as P8 and P9, only partially share the same language; While some participants, such as P2 and P5, have completely different languages. Moreover, the same pattern could be designed for different tasks by different participants. For instance, T1-3 was not only designed by P2, P7, and P12 for Task1, but also by P1 and P12 for Task4. No matter how similar or different each user's spatial pattern language may be, the vocabularies (or patterns) used by these languages are all included in Table II. With this information identified and specified, the micro-office's AI system could record the language of each user and thus, be able to "speak" the right language to the right user. This highly customized pattern language could not only make the robotic environment more supportive but potentially cultivate more trusted and intimate relationships such as friendship, partnership, and companionship between users and the environment. In other words, customized "spatial pattern languages" could potentially convey sociality to users.

TABLE II. SPATIAL PATTERNS GENERATED THROUGH THE CO-DESIGN PROCESS

| | 1, Ceiling-Embedded | 2, Perpendicularly Wall-Embedded | 3, Horizontally/Perpendicularly Wall-Embedded | 4, Wall/Furniture-Embedded |
|---|---|---|---|---|
| T1 | <br>P1 | <br>P3, P5, P6, P8, P9, P11 | <br>P1 (T4), P2, P7, P12, P12 (T4) | <br>P10 |
| T2 | <br>P3, P4, P4 (T1), P5, P7, P8, P12 | <br>P9, P10, P11 | <br>P2, P6 | |
| T3 | <br>P1, P5, P7, P8, P9 | <br>P2 | <br>P6, P11, P12 | |
| T4 | <br>P2, P11 | <br>P3, P5, P8 | <br>P7, P9, P10 | <br>P4, P6 |

## VI. EMPLOYING HRI PATTERNS FOR HUMAN-SURFACE INTERACTION DESIGN

In Section V, we identified the "spatial pattern language" for each user through the co-design process: the spatial pattern this micro-office should reconfigure into for different users when performing different tasks. However, each spatial pattern here is not a static spatial configuration:

First, there is a dynamic and interactive process when the robot surface moves from the "Starting Position" through a certain trajectory and finally reaches the "Ending Configuration."

Second, even at the "Ending Configuration," there are still subtle reconfigurations going on dynamically between the users and the robot surface. For instance, for T1, the robot surface probably needs to subtly adjust itself to the right height and position as a writing surface considering the different body sizes and writing habits of different users.

How do we design the movement (e.g., movement speed, timing, and trajectory) and embodiment (e.g., conveying affordances.) of this robot surface so that it can be perceived as helpful, welcoming, friendly, and collaborative? This is where the "Design Patterns for Sociality in HRI" [16] ("HRI Patterns" for short) comes in.

### *A. Four HRI Patterns for Sociality*

There are eight HRI patterns specified in [16], and for our design, we employed four of them considering their appropriateness for our prototype and scenario: "Initial Introduction," "Didactic Communication," "In Motion Together," and "Physical Intimacy."

"Initial Introduction" is a pattern that uses "a largely scripted and conventionally-established verbal and behavioral repertoire" to recognize the other and show politeness [16]. Thus, we went through the HRI literature to see how robotic furnishing showed recognizance and politeness when it met a user for the first time. A common strategy we found is that the robot always initiates its movement to acquire the user's attention, and then pauses a few seconds before moving again to show politeness [21, 23].

"Didactic Communication" is a pattern for "one-way communication of information, situated in a context where each party has the motivation to remain engaged" [16]. After our robot surface catches the user's attention, we could use this pattern to continue social communication. In robotic furnishing literature, one-way communication is commonly achieved through the proactive, autonomous movement of the robot and the affordances offered by the robot's physical embodiment [21, 22, 23].

"In Motion Together" is a pattern that "involves aligning one's physical movements with others" [16]. After our robot surface sends a one-way signal to the users, the movement of our robot surface should be aligned with the user. A common strategy used in robotic furnishing projects is that the robot's movement is determined by the user's reaction [21, 22, 23, 24]. For instance, if a user raises his/her feet, a robotic ottoman will move under the user's feet; if a user doesn't raise his/her feet, the robotic ottoman will gently nudge the user [21].

Finally, "Physical Intimacy" is a pattern that encourages physical contact between users and robots [16]. This is also a common strategy used in robotic furnishing projects [21, 22]. For instance, users put their feet on the robotic ottoman [21] and sit in robotic chairs [22].

### *B. Designing Human-Surface Interaction through HRI Patterns*

We used the spatial pattern T1-2 as an example to show how the four HRI patterns could unfold through a spatial pattern in our scenario:

1) *When Joanne begins looking for a suitable work surface, a wall-embedded robot surface starts to autonomously slide and bend towards Joanne. Before it reaches the position of a horizontal writing surface, it stops for 2 seconds to show politeness* ("Initial Introduction").

2) *Joanne recognizes the hard surface mounted at the end of the soft robot surface as suited to the writing task. The robot surface continues to move towards the horizontal position* ("Didactic Communication").

3) *If Joanne moves closer to the robot surface, the robot surface will subtly rest on her lap to fulfill its function as a writing surface* ("Physical Intimacy" & "In Motion Together")*; If Joanne does not move closer, the robot surface will keep swinging slightly to catch her attention* ("In Motion Together").

4) *After the meeting with clients is over, Joanne moves away from the robot surface and it autonomously goes back to its initial, vertical, wall-embedded position* ("In Motion Together").

We invited 6 college students (ages 19-34, 5 FM, 1 M) to experience this human-surface interaction through a writing task. Each participant was invited into a room with only a chair and a wall-embedded robot surface. Then the participant was given a piece of paper to do a simple writing task. Although the spatial pattern employed in this study was not exactly the same as T1-2, it did share the same human-surface interaction design we described above. Please see this video [34] as a visual illustration of our interaction design and possible user reactions.

With these HRI patterns integrated into each spatial pattern in Table II, our "spatial pattern languages" identified in "Section V" have evolved into pattern languages that convey sociality through both spatial and interaction patterns. In these new pattern languages, the spatial reconfigurations are intertwined with users' interaction with them, which together convey sociality (e.g., helpfulness, welcome, friendliness, and collaboration) to users as an integrated whole.

## VII. Discussion

To begin the discussion, we first would like to address the explorative nature of this work. We focus on the design exploration of SIREs through a pattern-based approach. This includes the user-centered approaches to generate new patterns and the employment of existing patterns. We are not focusing on the validation of the spatial or HRI patterns we generated or employed in this paper. After all, validation of a design pattern requires longitudinal studies that evaluate user preferences and the pattern's power to coexist with people in everyday life [15, 16], which is not an easy criterion to meet for either spatial or HRI patterns.

Second, in this paper, we try to focus on the differences between SIREs and IEs (e.g., "sociality," "physical embodiment," "robotic movement," and "spatial reconfigurations") and discuss how we could design these "differences" through the pattern-based approach. However, as shown at the beginning of the literature review, there are many things SIREs and IEs share in common including "intelligent AI systems," "interaction modalities," "ambient environment control," etc. We did not discuss the design of these "common aspects" not because they are not important, but because SIREs could, we believe, borrow many of the design principles and strategies from IEs for the design of these common aspects [18].

Finally, we use this paper to explore the opportune marriage between "spatial patterns" and "HRI patterns" into one pattern language for conveying sociality to users. "Spatial patterns" and "HRI patterns" have always been conceptualized as patterns of different categories with their own pattern languages. Through this work, we see that they can be "spoken" in one language in the case of SIREs. Arguably, there could be many other ways to integrate "HRI patterns" and "spatial patterns" besides what we presented here. Nevertheless, we see this "pattern marriage" inevitable as our environments become more and more intelligent, reconfigurable, and interactive.

## VIII. Conclusion

In conclusion, we argue, based on theoretical and empirical evidence, that robotic environments can be perceived and interacted with as socially intelligent agents. Moreover, we argue that such Socially Interactive Robotic Environments (SIREs) can be designed through a pattern-based approach that integrates both spatial and interaction designs. In this pattern-based design approach, we generate new design patterns and employ existing design patterns for spatial and interaction designs of SIREs. Our goal is to create pattern languages that can convey sociality to individual users or user groups through the embodied interaction of SIREs including spatial reconfiguration, robotic movement, and physical embodiment.

## IX. Contribution

We summarized the key contributions of this paper in the following three points:

First, we introduced Socially Interactive Robotic Environments (SIREs) to the IE communities through empirical evidence and theoretical support. SIREs could potentially become a new research area for IE communities.

Second, we proposed a pattern-based approach for designing SIREs and explored its plausibility through the design exemplar of a partner-like micro-office. This very practical pattern-based approach can be applied to the design of many smart, reconfigurable spaces such as smart homes, smart vehicle interiors, smart offices, and smart nursing homes.

Finally, we illustrated for the first time, to the best of our knowledge, that how "Spatial Patterns" and "HRI Patterns" could merge into one pattern language for conveying sociality. This opens a new design research direction where patterns of different categories can form one language to convey a coherent message to users. For instance, could we integrate HCI, HRI, and spatial patterns together for designing IEs or SIREs?

## X. Limitation

We observed the following limitations in this work:

First, because of the limited resource and Covid-19 situations, we did not construct a robotic room prototype embedded with multiple robot surfaces to achieve different spatial patterns as shown in Table II. Thus, no user feedback was gathered regarding these interactive spatial patterns.

Second, although we considered politeness, helpfulness, collaboration, and friendliness of this partner-like office in the design process, we didn't consider the personality of this "partner." Could this office be optimistic, curious, or shy? Personality is an important factor to consider for designing social interactions.

## XI. Future Work

We are actively exploring what SIREs could contribute to our everyday life and how we could design SIREs. More specifically: *How could a reconfigurable environment benefit people when it becomes our friends, companions, partners?* and, *What kinds of roles we would like SIREs to play in different situations and contexts?* Currently, we are conducting the following two studies:

- We use VR to simulate the socially expressive behavior of a bio-robotic wall and evaluate whether such a SIRE could be restorative for people in confined spaces.
- We use VR to simulate the reconfigurable in-car environment of smart vehicles and evaluate if such a SIRE could improve emotional driving experiences which are closely related to driving efficiency and safety.

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