How Do We Want to Interact with Robotic Environments?

User Preferences for Embodied Interactions, from Pushbuttons to AI

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ABSTRACT

In this paper, we report on user preferences for different interaction modes from pushbuttons to AI when interacting with robot surfaces—malleable, adaptive, physical surfaces that spatially reconfigure interior spaces within the built environment. With global mass-urbanization, micro-homes and offices are proliferating, we envision the utility of robot surfaces in reconfiguring compact space into "many spaces" supporting and augmenting human activity. Users in a lab study (N=12) were asked to consider robot surfaces of our design, used in conjunction with common design tasks performed in a micro-office—specifically, which interaction modes were preferred at five key instances (we call them "scenarios") over the duration of the task. We found that, for the five scenarios, participants' preferences were split between AI-controlled and user-controlled interactions because of the contexts of different scenarios and the complexity, accuracy, discreetness, and feedback speed of different interaction modes. Our research informs the design of increasingly architectural and spatial human-AI interactions in everyday life.

KEYWORDS

Human robot interaction; robotic architecture; AI-embedded robot surface; compact office; user preferences.

1 Introduction

The frontiers of human-computer and human-robot interaction (HCI and HRI) are extending to architecture space, reconfiguring our everyday environments for various activities (Fender and Müller 2019). Robotics is emerging as integral to spatial interactions; however, robot developments for use in the everyday spaces we live in—home, hospital, school, and office—have often focused more on humanoid robotics as replacements for human servants (e.g. Cory D and Breazeal 2008) rather than supporting and augmenting human capabilities by forming a collaborative environment (Wang, et al. 2019). Nevertheless, in recent years, there has been increasing interests in non-humanoid robotics manifested as robotics-embedded furniture and building systems within everyday spaces (Brauner, et al. 2017; Green, 2016; Gross and Green 2012; Hoffman 2015; Hoffman and Ju 2014; Ju and Leila 2019; Schafer, et al. 2014; Sirkin, et al. 2015; Spadafora, et al. 2016; Verma, et al. 2018). Such robotic artifacts combined with the interior spaces they cohabit are intended to create cyber-physical environments that assist users in daily activities (Sirkin, et al. 2015; Verma, et al. 2018), augmenting the capacity of users to perform tasks (Schafer, et al. 2014; Verma, et al. 2018) and even provide them with a semblance of emotional and social support through carefully designed human-robot choreographies (Hoffman 2015; Ju and Leila 2019; Schafer, et al. 2014; Sirkin, et al. 2015; Verma, et al. 2018). In addition, some design researchers developing non-humanoid robotics have been developing "robot surfaces" as tangible, shape-changing interfaces mediating human-computer interactions (Bosscher and Uphoff 2003; Nakagaki, et al. 2019; Rosen, Nguyen, and Wang 2003; Stanley, Hata, and Okamura 2016). But these robot surfaces are rarely developed at a larger "environmental" scale or designed as space-making devices (e.g., robotic partitions, ceilings, floors, etc.).

Aligned with this expanded vision (Oosterhuis and Bier, 2013) are novel, space-making, robot surfaces (Sirohi, et al. 2019; Wang, et al. 2019; Wang and Green 2019) which are characterized as malleable, adaptive, physical surfaces that reconfigure interior spaces, supporting and augmenting human activity (Wang, et al. 2019; Sturdee and Alexander 2018). These robot surfaces can be embedded in or mounted on ceilings or walls, or be free-standing, and can reconfigure one spatial volume into "many spaces" matched to human activities. We envision such robot surfaces having application to confined spaces such as micro-apartments and micro-offices (in costly real estate markets and/or where land is limited), to disaster relief shelters or scientific outposts, to spacecraft and space habitation, and to fully autonomous vehicles (Sirohi, et al. 2019).

To provide a sense of robot surface behaviors, we present (in Table 1) five "scenarios" for the use case of designers working in a micro-office. Here, we are not implying that our robot surfaces were only developed for designers or micro-offices. Instead, this use case serves as a tool to speculate and acquire insights for potential user interactions with this new piece of technology. The compact, physically confined spaces are found increasingly in costly real estate markets and the densest cities due, especially, to both global mass-urbanization and the scarcity of land for development. These five scenarios characterize common work activities of the design-professions based on former observational studies and literature reviews of designers at work (Wang and Green 2019). Our research team focused on design activities for the scenarios given their mix of digital and manual tool usage and collaborative nature. Design activities encompass wide-ranging kinds of office work, so studying these interactions arguably generalizes to many kinds of collaborative work environments. In preparing these five scenarios, we tested with users the question, *What kind of human—robot-surface interactions would users prefer most in these scenarios, and why?* For screen-based and other relatively structured tasks, researchers have offered general design guidelines for AI-embedded interface design (Amershi, et al. 2019; Höök 2000; Horvitz 1999; Jameson 2008; Norman 1994); but in the wild frontier of spatial human–surface interaction, such questions demand considerable attention.

To address the research question, we conducted a user study for the micro-office use-case using a robot surface prototype of our design. Conducted in our lab with 12 design major students, our study focused on user experiences with this tangible, interactive system. Participants walked through ("user enactment" by Odom, et al. 2012) five scenarios (as per Table 1) and selected their preferred interaction modes or proposed new interaction modes as they saw appropriate at key instances in the unfolding activity. Through qualitative analysis, we found significant interaction-mode preference differences for different scenarios and probed the reasons beneath these differences.

2 Related Work

Our research of human–robot-surface interaction is informed by four topics explored in the literature: *Computer-Supported Cooperative Work* speaking to the environment and context where the robot surface is applied; *Robots that Work with Humans* speaking to our interaction design for robot surfaces and users; *Architectural Robotics* speaking to the capacity of robot surfaces to form physical space serving human needs and wants; and *Shape-changing Interfaces* speaking to the robot surface as interface.

2.1 Computer-Supported Cooperative Work

CSCW communities have been exploring computer-supported cooperation for collaborators in different locations through groupware (Lee and Paine 2015; Domova 2013; Campos, Ferreira, and Lucero 2013; Sellen 1992; Tanner and Shah 2010), mixed reality (Billinghurst, et al. 2001; Hanaki, Tansuriyavong, and Endo 2002), and virtual reality (Gauglitz, et al. 2014; Greenhalgh and Benford 1995). Our work could arguably be characterized as an exploration of "computer-supported cooperative work environment" in that collaborators in our scenarios (Table 1) are working together in a computer-supported office with robot surfaces. The CSCW literature provided us many insights of the inter-human cooperative working process such as "face-to-face gestural interactions" (Bekker, Olson, and Olson 1995) and "workspace informal communications" (Sauppé and Mutlu 2014; Whittaker, Frohlich, and Jones 1994). These insights were useful when we designed interactions for our robot surfaces (Table 1). Our work is novel for CSCW research in that the co-workers in our scenario are cooperating in the same physical space, and the work environment reconfiguration occurs physically (i.e. moves physical mass, and not only bits) to support user activities.

2.2 Robots that Work with Humans

This research benefits from the well-established body of literature on human-robot interaction (Goodrich and Schultz 2008), social robotics (Bosscher and Uphoff 2003; Fong, Nourbakhsh, and Dautenhahn 2003; Eklundh, Green, and Hüttenrauch 2003; Tapus, Maja, and Scassellatti 2007), and the ubiquity of robots (Chibani, et al. 2013; Chibani, et al. 2012; Kim, et al. 2007), drawing inspiration especially from research literature (Schafer, et al. 2014; Sirohi, et al. 2019; Wang and Green 2019) focused on applications of robots in homes (Forlizzi and DiSalvo 2006; Kidd and Breazeal 2008; Prassler and Kosuge 2008), and healthcare (Kazanzides, et al. 2008). Furthermore, our research draws inspiration from research in robotics focused on applications that influence how human beings approach tasks in work environments (Solly, et al. 2014; Fasola and Mataric 2012; Zawieska and Duffy 2015). Here, the explicit goal is for the robot to incite the user into a different state of activity or consciousness than would not be achieved if the robot were not present. We report here on how robot surface interactions might be made functionally effective, socially supportive, and emotionally encouraging to users in a confined workspace.

2.3 Architectural Robotics

We characterize robots that form and reconfigure spaces as "architectural robotics," an emerging subfield in robotics and architectural design (Green 2016). Architectural robotics is, in part, inspired by Malcolm McCullough's vision of "a tangible information commons" in which a "richer, more enjoyable, more empowering, more ubiquitous media become much more difficult to separate from spatial experience" (McCullough 2013; McCullough 2014). Architectural robotics follows, moreover, from the concept of Christopher Alexander et al. of a "compressed pattern" room as elaborated in A Pattern Language (Alexander, Ishikawa, and Silverstein 1977), conceived for the built environment but since applied to cyber-human systems (Gamma, et al. 1995) and human-robot interaction (Kahn, et al. 2008). In a compressed pattern room, all the functional rooms within a typical building are essentially formed within a single volume (i.e. one room) that can physically reconfigure.

Following from Alexander's compressed pattern room, we envision a robot surface physically reconfiguring (with embedded lighting, audio, sensors, and touch surfaces) to arrive at shape-shifting, functional states supporting and augmenting human activities. Drawing from the scenarios (as per Table 1), our robot surfaces configure, in one room, a meeting place, a private working space, a presentation room, and a place of repose. Architectural robotics speaks to the envisioned capacity of a robotic, physical environment to shape wide-ranging human activities.

2.4 Shape-changing Interfaces

Robot surface (Ortega and Goguey 2019) and shape-changing interface (Sturdee and Alexander 2018) are both cyber-physical interfaces which can reconfigure physically. Many shape-changing interfaces, however, are designed specifically for communicating information to users (e.g., physical information displays) and offering dynamic affordances (e.g., shape-changing buttons) (Rasmussen, et al. 2012), whereas robot surfaces can be designed to reconfigure the spatial envelops and redefines the spatial affordances for human activities. According to the literature reviews of shape-changing interfaces, architectural applications (Rasmussen, et al. 2012; Sturdee, et al. 2015), user experiences (Rasmussen, et al. 2012; Rasmussen, et al. 2013), and user perceptions (Rasmussen, et al. 2012), are going to be the future research direction of shape-changing interface. Thus, the investigation into users' preference of space-making robot surfaces reported here is at the frontier of shape-changing surface research.

3 Continuum Robot Surface Prototype

As shown in Figure 1, the continuum robot surface is a 2-inch-thick foam panel sectioned by six thin, plywood collars with three tendons running through 3D-printed place holders mounted to the collars. Three motors mounted at the top of the surface (see Figure 1) pull the tendons to reconfigure the surface in five different configurations that are established as a basic behavioral taxonomy: "rest position," "soft bend," "strong bend," "angled," and "twisted" as shown in Figure 2. Details of the experimentation with the surface configuration and control is reported in Sirohi, et al. 2019. This project explores compliant robot surfaces featuring remote actuation of tendons embedded within the surface structure for the following three reasons:

First, as characteristic of continuum robots, tendon-driven continuum robots feature smooth, compliant, and continuously bending bodies inherently suited to operation in close proximity (including interactive and intimate contact) with humans.

Next, in addition to being well-suited to interactions with people, tendon-driven designs have the advantages of providing the strength to move surfaces that are both large and compliant.

Finally, another advantage of this design choice is that the actuators and their associated electronics can be kept away from the human co-habitants of the shared environment.

The design decision of this specific tendon-driven mechanism (6 collars with 3 brackets on each) is informed by the testing results of the design iteration where tendons were pulled manually. We also tried several different motors and 3D-printed motor hubs (Figure 1) to achieve the right speed and strength of the actuating system.

4 Physical Prototype In-lab Study

For this study, we invited to our lab, through convenience sample, 12 university undergraduates and graduates with a design major (interior design, fashion design, and UX design; 5 undergraduates, 7 graduates; ages 18-32; 4 FM, 8 M).

Participants provided feedback on how they would like to interact with the robot surface when performing different design tasks and the reasons for their preferences.

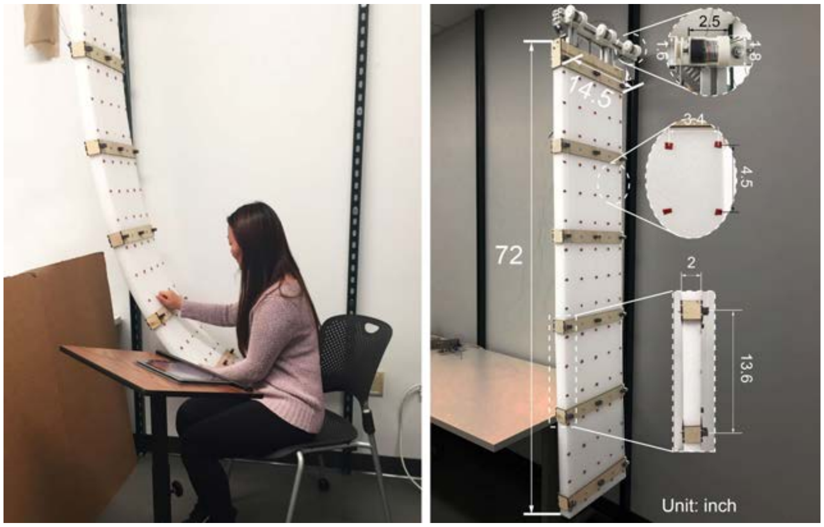


Figure 1. A participant performing task 1 ("Note Taking") with the robot surface prototype in the lab.

4.1 Study Design

For this exploratory, qualitative study, the 12 designers were asked to evaluate human—robot-surface interactions in our lab. The primary interest of this study was to learn which interaction modes are preferred for this robot surface within five different scenarios, and why? Since "users have a very hard time predicting how to interact with future systems with which they have no experience" (Nielsen 1994), we proposed four common interactions (Button, GUI, Voice Command, Proximity Sensor) and one AI-controlled, autonomous interaction (Human Activity Recognition), as defined in Table 2, and asked participants to experience these interactions with robot surfaces.

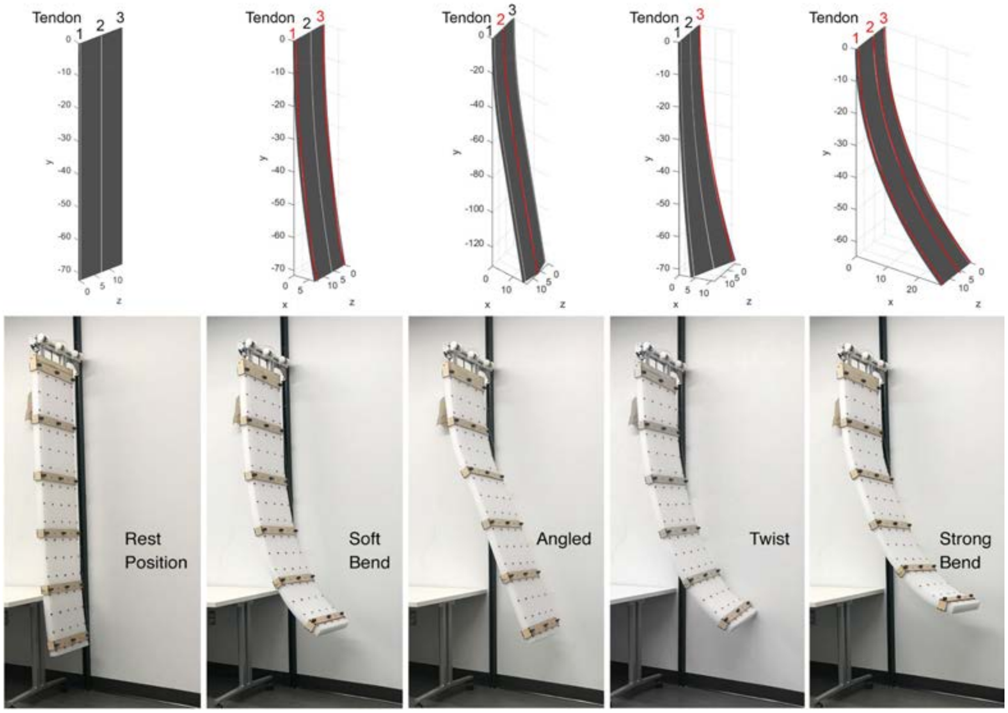
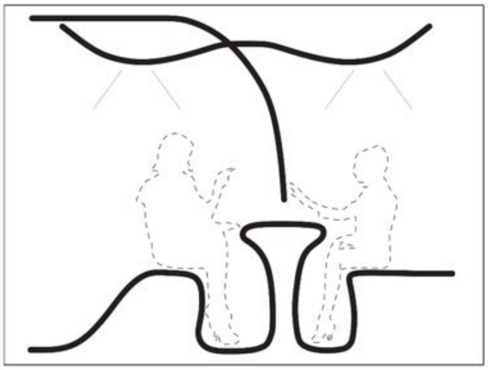
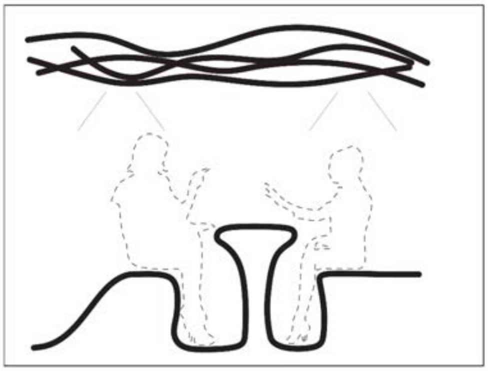
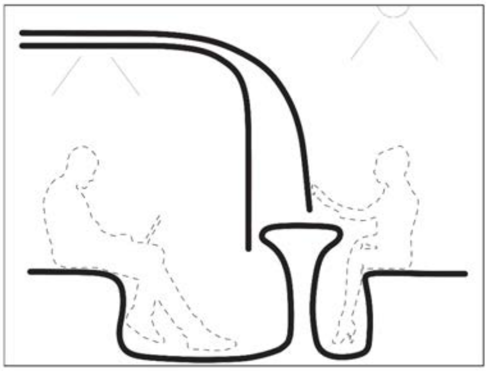
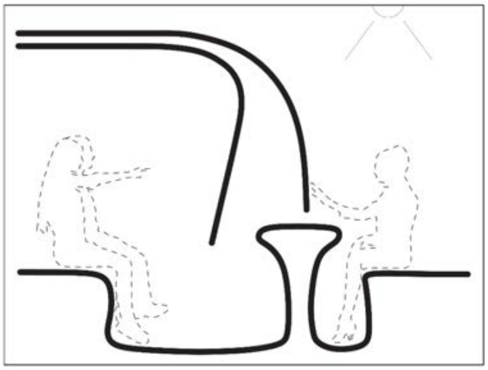


Figure 2. Top row: simulation of 5 configurations, bottom row: prototype images of configurations. Red curves represent tendons being pulled to achieve corresponding configurations.

Scenario	Conceptual Diagram	Task Description by Scenario
Scenario 1: Note Taking		When designers receive comments from clients, reviewers, and fellow designers, they usually take notes for future reference and discussion. Robot surface could help to provide a writing surface (such as a tablet) for the note-taking tasks.
Scenario 2: Shape & Atmosphere Simulation		Designers constantly need sources of inspirations during ideation process. Such inspiration can be an image, a piece of music, a video, a narrative, a conversation, etc. In these scenarios, robot surfaces could use the embedded multimedia systems (e.g., sound, light, and physical movement) to change the atmosphere of the working space. The multimedia environment could serve as sources of design inspirations.
Scenario 3: Space Division		Meetings with clients or reviewers could sometimes be interrupted by something urgent (e.g., urgent email, urgent phone call, family emergency, etc.). In these cases, designers need privacy to handle these situations. Moreover, design activities always consist of team working and individual working. In either case, robot surfaces could devide the space to create privacy for private workings.
Scenario 4: Presentation		Designers give presentation constantly during design iterations, sometimes to clients and sometimes to reviewers. Robot surfaces could help to create a presentation space by temporarily providing big screens, control platforms, and right lighting environment.

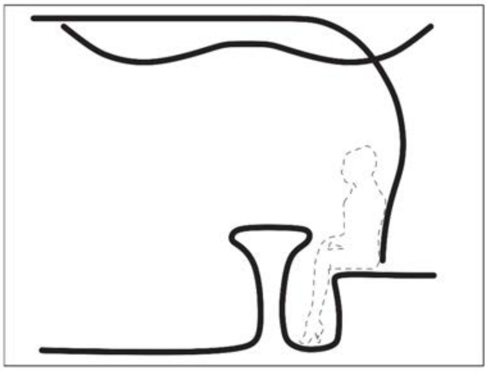
Scenario 5: Body Support		Designers work very hard espeically when deadlines are approaching. Many designers work, eat, and even sleep in the design studio. Thus, a comfortable and ergonomic body support, which can be provided by the robot surface, is alway welcome and helpful in design studios.

Table 1: Five "Scenarios" unfolding over the course of common design tasks.

4.1.1 User Enactment and Semi-Structured Interview

We conducted user enactments (Odom, et al. 2012) by which users "enacted" a scripted scenario, allowing researchers to "observe and probe participants, grounding speculations about how current human values might extend into the future" (Odom, et al. 2012). This user experience was followed by semi-structured, in-person interviews with each participant, rewarded a $10 (USD) Amazon gift card for participating in this 40-minute study. One at a time, participants visited our lab fashioned as a compact, micro-office environment with chair, table, shelves, and a computer (see Figure 1). In this office setting, we added a functional, button-controlled robot surface prototype of our design measuring (as shown in the same figure). Participants performed work tasks with the prototype as a means to experience human—robot-surface interactions as afforded by the surface installed in the work environment. By asking participants to engage in the prescribed work tasks that included the five scenarios (Table 1), we allowed the participants to experience both the physical setting of a typical office together with the intervention of our robot surface.

The robot surface configuration used in this user study is initially the "soft bend" (shown in Figure 1) which produces a bend slightly upwards, providing a working surface for writing and reading. In our study, the experimenter controlled the surface using buttons hidden from the participants to simulate different interaction modes for the participants as per the "Wizard of Oz" technique (Dow, et al. 2005).

Interaction Name	Interaction Description
Interaction 1: Button (user-controlled)	By pushing the button on the desk, the robot surface will be activated and bend down. By pushing the button again, the robot surface will stop moving.
Interaction 2: Voice Command (user-controlled)	By voice commanding Amazon Echo (e.g. "Alexa, provide me a tablet!"), the robot surface will bend down. By voice commanding Amazon Echo (e.g. "Alexa, stop!"), the robot surface will stop where you want it.
Interaction 3: Human Activity Recognition (AI-controlled)	In your office, an AI system recognizes your activities using cameras. The AI system is meant to help you with your tasks, anticipating your needs. The AI system is observing your behavioral patterns and trying to understand what you're doing now and what you will do soon. The robot surface will be activated and stopped automatically by AI to assist your work.
Interaction 4: Graphic User Interface (user-controlled)	By using a graphic user interface on a touch screen embedded in your worktable, you can control the robot surface. For instance, if you want to bend the robot surface, you can select "strong bend" on the screen.
Interaction 5: Proximity Sensor (user-controlled)	There are proximity sensors on the robot surface. You put your hand close to the sensor and it starts to bend. You put your hand close to the sensor again and the robot surface stops where you want it to be.
Interaction 6: Anticipatory NLP (AI-controlled, proposed by participants)	In your office, the AI system is listening to your voice and searching for key words. To anticipate your needs, the AI system is trying to understand what you're doing now and what you will do soon. The robot surface will be activated and stopped automatically by AI to assist your work.

Table 2: Six Interaction Modes.

4.2 Procedure: Step-by-step Study Protocol and Interview Questions

1. First, we introduced this robot surface prototype to the participant by verbally describing its structures, functions, and potential applications.
2. Second, we presented a video showing five different configurations that could be assumed by the robot surface prototype, including "Resting Position," "Strong Bend," "Soft Bend," "Twist," and "Angled." This video helped the participant better understand the functionality of the robot surface and the context of the study.
3. Third, we introduced five ways in which people could interact with the robot surface: Buttons, Voice Command, Human Activity Recognition, GUI Interface, and Proximity Sensors, as specified in Table 2.
4. Fourth, we introduced five scenarios (Table 1) and asked the participant to role-play, initially, scenario 1. For scenario 1 (i.e. notetaking during a conversation with a client), the participant performed the task with the robot surface prototype in our lab (Figure 1). Using the "Wizard of Oz" technique [12], we simulated all five interactions, one by one, for the participant while he/she is performing the given task. We then asked the participant to choose her/his most preferred interactions or propose new interactions.
5. Fifth, after experiencing the five interactions through role-playing scenario 1, the participants were each presented with videos, pictures, and narrative descriptions of scenarios 2, 3, 4, and 5 (Table 1). For each scenario, after watching the corresponding videos and pictures with narratives, the participant chose his/her favorite interactions or propose new interactions if none of the 5 interactions is preferred. The participant then offered reasons for his/her preferences.
6. Sixth, our study was followed by a semi-structured interview with three open-ended questions. Notes were taken to record answers offered by the participant. Question 1: *What is your impression of this technology?*; Question 2: *What are things you would improve?*; and Question 3: *What other use cases can you think of for this technology?*.

4.3 Qualitative Data Analysis and Results

Each participant was asked to choose their favorite interaction modes for each scenario. Some participants chose one or two interaction modes as their favorite, and others proposed new interaction modes for some scenarios since none of the five interaction modes was preferred. Figure. 4 shows how many times each of the five interaction modes was voted as the favorite one for each scenario by participants. The data is color coded with deeper blue representing more votes.

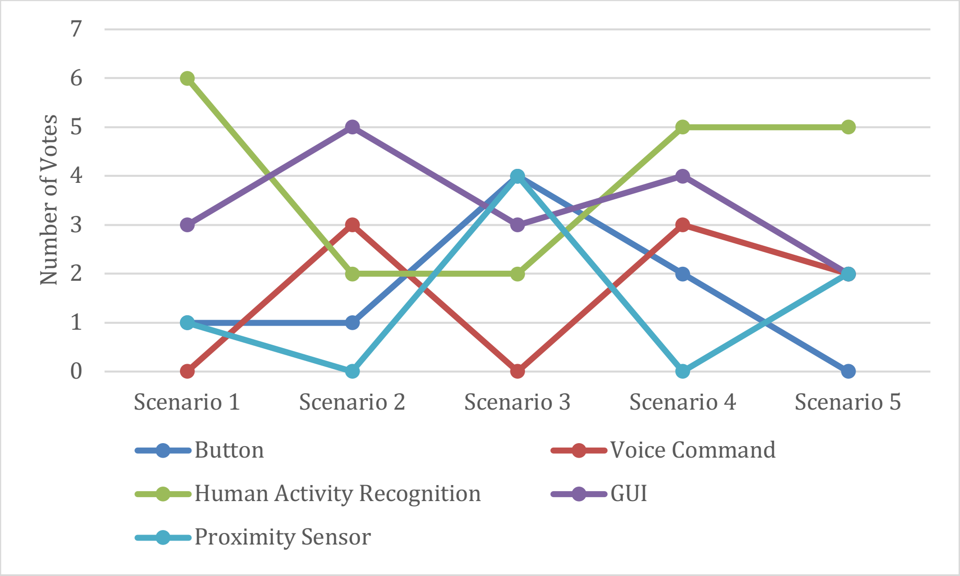


Figure 3: Number of Votes on Favorite Interaction Modes for Each Scenario.

4.3.1 Participants' Feedback on "Human Activity Recognition" (Interaction 3)

As visualized in Figure 3, the most preferred interaction mode overall for the 12 participants is "Human Activity Recognition," which was the most-voted interaction for scenarios 1, 4, and 5. Below are participants' feedback on this interaction, expressed as a list of written statements which, for us, captures what was communicated repeatedly by two or more participants.

1. The mental load using “Human Activity Recognition” is lower than other interaction modes; therefore, users are less likely to be interrupted in their tasks (as offered by Participants 1, 2, 3, 11, 12).
2. Human Activity Recognition is “most convenient” for accomplishing simple tasks, as the system’s intelligence saves the human user the chore of giving specific commands or instructions to the system (Participants 1, 6, 9, 10).
3. By capturing data coming with human body gestures as a control mode, more comfortable body support could be provided (Participants 5, 8, 11).
4. It is “discreet rather than distracting” to the user (Participants 7, 10).
5. The interaction process feels natural, as if the robot surface is the body-extension of oneself (Participants 2, 8).

Additionally, some participants were concerned that interaction by Human Activity Recognition might not be accurate enough (Participants 5, 8, 9), smart enough (Participant 10), or offering users sufficient control of the system (Participant 12).

4.3.2 Participants’ Feedback on “Graphic User Interface” (Interaction 4)

The second most preferred interaction mode for the 12 participants, overall, was “Graphic User Interface,” which was also the most voted interaction for scenario 2 and the second most voted interaction for scenario 1 and 4. Below are participants’ feedback on this interaction:

1. This interaction is relatively quiet, discreet, and not distracting (Participants 2, 5, 6, 10).
2. This interaction offers user control with enough many options (Participants 2, 12)
3. This interaction offers a simpler, easier, and familiar control over the system (Participant 8).

Additionally, participants 1, 4, 8, 10, and 12 suggested that they would like to see graphic sliders instead of only buttons for fine-tuning the robot surface’s bending angle and icons to tap as shortcuts to control predefined robot surface configurations. These are useful suggestions for us to consider for further user studies and prototype iterations.

4.3.3 Participants’ Feedback on “Voice Command” (Interaction 2)

The third most preferred interaction mode for the 12 participants was “Voice Command,” which was also the second most voted interactions in scenario 2 and 4. Below are participants’ feedback on this interaction mode:

1. Voice Command allows the user to give commands with the least effort while multi-tasking (Participants 6, 12).
2. Talking to a robot in front of other people is natural and straight forward (Participants 2, 9, 11).
3. Voice Command allows you to control freely with much more options than other interactions (Participants 2, 4, 12).
4. Language used to convey commands could convey specific meanings to the system (Participants 2, 3).

Additionally, participants 3, 10, 11, and 12 were concerned that talking to the robot surface might be disruptive to accomplishing tasks and human-human interactions. Furthermore, participant 2 mentioned that Voice Command might not be convenient while users communicated with someone else via the phone.

4.3.4 Participants’ Feedback on “Proximity Sensor” (Interaction 5)

“Proximity Sensor” overall ranked the 4th most preferred interaction mode, and. was also one of the two most voted interaction for scenario 3. Participants 1, 5, 6, 7, 10, and 11suggested that Proximity Sensors are a direct, reliable, and tangible interaction. Participants 7 and 12 suggested that it is natural to use Proximity Sensors for something urgent or time sensitive. Meanwhile, participants 2 and 10 reported that Proximity Sensors could cause interference and distraction given that users need to keep watching the robot surface before touching the sensor a second time to stop it. Finally, Participant 12 suggested that Proximity Sensors offer very few options to control the surfaces.

4.3.5 Participants’ Feedback on “Button” (Interaction 1)

“Button” ranked the fifth most preferred interaction mode in total votes and was one of the two most voted interactions for scenario 3. Participants in favor of this interaction suggested that buttons are simple, straightforward, and intuitive (Participants 5 & 12). Participants 1 and 6 also mentioned that buttons were more discreet and less disruptive in human-human interaction, especially in the occasionally awkward social situation that at times occurs at work. Meanwhile, two participants argued that buttons are too cumbersome and not “that beautiful” (Participants 2 & 3).

4.3.6 Participants’ Identification of Interaction Modes to Add/Consider

Some participants recommended other interfaces that might suit the five scenarios described. “Anticipatory Natural Language Processing” (Interaction 6, Table 2) was a new interaction mode proposed by multiple participants (5 out of 12 participants) mostly for scenario 3. Participants in favor of this interaction suggested that an interaction based on the system picking-up verbal cues instead of requiring direct commands issued by the user makes life easier (Participants 1

& 9). Four participants also argued that it feels natural in situations such as captured in scenario 3 (Participants 3, 4, 9, & 11). We believe that this is an important interaction mode should be carefully considered for future design.

Two participants proposed “Pressure Sensing” for scenario 5, where they argued that the robot surface should provide back support intelligently by adjusting its curvature ergonomically based on the amount of pressures received by the AI system from the sensor grid embedded in the robot surface. One participant proposed, as well, Joystick” for scenario 1, as he/she preferred “a more tangible version of GUI interface.” We believe these are all inspiring ideas for designing human-surface interaction.

5 FINDINGS AND DISCUSSION

We now consider how our results (4.1) provide insights for robot surface interaction design in a compact, interactive working space, and (4.2) inspire future research for complex human-surface interactions including those where AI is embedded in the built environment.

5.1 Insights for Robot Surface Interaction Design

The interaction modes will be discussed here include AI-controlled interactions (Human Activity Recognition, Anticipatory NLP, and Pressure Sensing) and user-controlled interactions (Button, GUI, Voice Command, Proximity Sensor, Joystick). Here, AI-controlled interactions refer to the interaction modes where the AI-embedded system automatically gathers information from the users (e.g., from users’ working activities, verbal cues, and body postures), analyzes the data, and makes decisions on activating or reshaping the robot surface for users. User-controlled interactions refer to the interactions where users give direct command to the system.

1. Users prefer AI-controlled modes for the simpler scenarios (e.g., Scenario 5 “body support”) which require fewer control options or complexities. For simple scenarios, people would like “the system’s intelligence to save the chore of giving specific commands to the system” (as commented by participants 1, 6, 9, 10). On the other hand, Scenario 2 (“Shape & Atmosphere Simulation”) is a complex task requiring more control of alternative surface reconfigurations, which is perhaps why users choose “GUI Interface” and “Voice Control” to acquire more control over the system (as commented by participants 2, 3, 4, 12).

2. Users prefer AI-controlled modes for scenarios where they prefer the human-surface interactions happen in discreet, or a natural way with instant feedback as if the surfaces are extensions of oneself. For instance, in scenario 1 and 4, users want the tablet or presentation screen to be delivered by the surface without interrupting the conversation (participant 1, 3, 6, 10, 11); in scenario 3, users want the robot surface to divide the space automatically after they excused themselves for urgent emails or phone calls from the clients (participant 3, 4, 9, 10); in scenario 5, users proposed the “Pressure Sensing” interaction modes so that they can get instant feedback and constantly change the robot surface curvature with a more comfortable body position (participant 1, 3). However, in some scenarios (scenario 3 and 4), “GUI interface” can also be described as “relatively discreet, quiet, and not distracting” (Participants 2, 5, 6, 10).

3. For the controls that cannot be easily specified by direct commands (such as the detailed curvature of the robot surface), users prefer the system to gather detailed information by itself and then reconfigure the surface properly. For instance, in scenario 5, users prefer the AI system to gather pressure data automatically and reconfigure the robot surface curvature to fit body postures, since they believe it is easier and more precisely controlled in this way (participant 3, 5, 6, 8). For controls that can be easily specified and described, however, users prefer “Voice Command” when “discreetness” is not part of the equation, since it is natural and straightforward (participant 2, 4, 9, 11, 12).

Nevertheless, there are some concerns with AI-controlled interactions, including the system’s control accuracy (participant 5, 8, 9, 11) and its ability to correctly interpret the situation (participant 2, 9, 10, 11). In short, there are trust issues with the AI-controlled system. On the other hand, users are usually more familiar with and confident about user-controlled interaction modes. Designers should carefully take these aspects into consideration when designing spatial human-surface interactions.

5.2 Future Research

Because of the limited time we could devote to each participant-session in our lab study and the limited number of interaction modes participants could remember when making a choice, we elected with hesitation to not include semi-autonomous interaction modes as an option in our studies. Interestingly, users didn’t propose any semi-autonomous interactions either in the study. We intend to pursue this research direction in the future as we intensively conduct further user studies with a full-functioning system of multiple robot surfaces (Houben, et al. 2016). We will explore user preferences of semi-autonomous interfaces with built-in verification steps (Höök 2000; Norman 1994), direct manipulation constructs (Horvitz 1999), and predictable AI behaviors (Amershi, et al. 2019). We believe a seamless integration of AI-controlled, user-controlled, and semi-autonomous interactions can be the next step of spatial human-surface choreography in an interactive space.

Informed by our findings, we will construct a compact office space with up to three fully functional robot surfaces enabling different interactions for pre-defined scenarios. The results of the studies reported here will inform the interaction modes we will implement in the next prototype. Additionally, the number of robot surfaces (one, two, three?) will also be a variable intended for our further study. We will invite participants with different backgrounds to perform defined scenarios with, and without the robot surfaces to again characterize human–robot-surface interactions (user experience, usability) and also, this next time, compare task performance (efficacy) under treatment and control conditions (e.g. number of errors made by participants, number of examples produced, quality of examples produced as judged by experts).

5.3 Speculative Visions: Robot Surfaces in Our Everyday Life

As mentioned at the beginning of this article, robot surfaces can interactively and adaptively reconfigure a compact space into “many spaces,” supporting and augmenting human activity. We envision a future where robot surfaces are widely applied in our everyday life for many kinds of compact spaces. Figures 4, 5, 6, and 7 show how multiple robot surfaces can be applied in smart vehicles, compact offices, smart homes, and smart nursing homes. For each of these scenarios, user interactions (e.g., interaction modes, autonomy levels, etc.) could and should be carefully investigated through user studies as presented in this paper. Arguably, this is not an exhaustive list of potential robot surface applications. There are many other speculative scenarios for robot surface applications in a future where interactive and adaptive robotic environments become an integral part of our everyday life.

Figure 4: Robot surfaces Envisioned in Smart Vehicle.

Figure 5. Robot surfaces Envisioned in Compact Office.

Figure 6. Robot Surface Envisioned in Smart Home

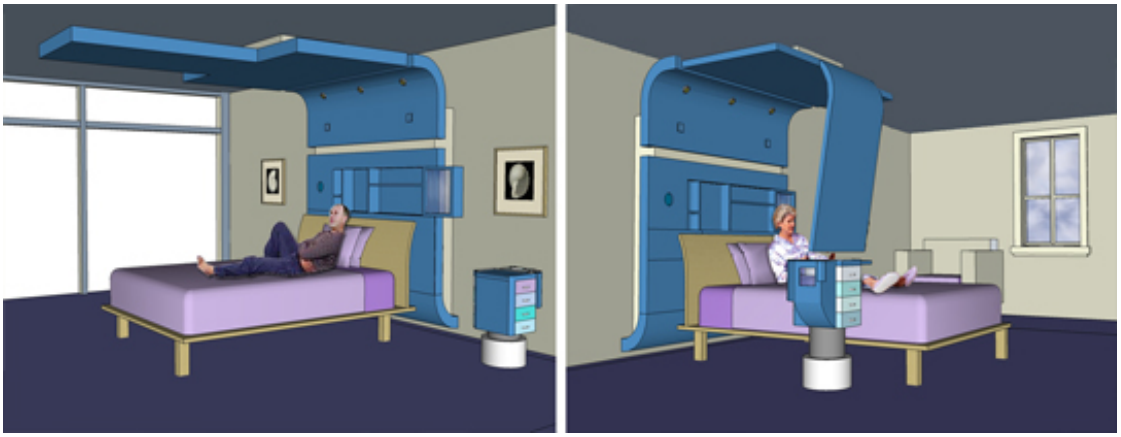


Figure 7. Robot Surface Envisioned in Smart Nursing Home

6 Limitation

There are several limitations for this study:

First, the 5 scenarios in Table 1 only represent a small aspect of design tasks. Some scenarios are more individualized such as scenario 5 (body support) while some are more collaborative such as scenario 4 (presentation). Moreover, some scenarios (e.g., scenario 1) can be either individual or collaborative. Collaborative and individual activities can sometimes result in conflicting situations for the responsive robot surface which complicates the interaction scenarios.

Second, the small samples size of 12 participants would benefit from additional future studies.

In addition, this study is done through Wizard of OZ technique where an experimenter emulated AI interaction for users. Further studies with fully functional, AI-controlled robot surfaces can provide more insights.

7 Conclusion

In this paper, we identified user preferences for human–robot-surface interactions, from pushbuttons to AI, within a compact (small volume) physical space through a qualitative, in-lab study using a robotic surface of our own design. The outcome of our study may be viewed as validation of what Gordon Pask and Nicholas Negroponte suggested decades ago (Pask 1969; Negroponte 1975); that intelligence in architecture emerges through socially intelligent interaction when both sides of the interaction are intelligent.

Our design and the outcomes of our study provide architects, roboticists, and human-computer interaction researchers an understanding of the complex intelligence that emerges through interactions between humans and AI-embedded architectural robotics. Specifically, the outcomes of our user study offer designers knowledge about user preferences for shape-changing surfaces and spaces with different autonomy levels as found in realistic, working-life scenarios. More broadly, this research informs a deeper understanding of our coexistence with robot and AI-embedded built environments. Such environments manifested as physically reconfigurable micro-offices, micro-apartments, and assistive care facilities are likely to proliferate as society continues to mass-urbanize, grow older, and grow in numbers.

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