SPACE-MAKING ROBOTS AS "AGENTS"

A DESIGN PARADIGM BASED ON HUMAN-AGENT INTERACTION

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ABSTRACT

This dissertation explores the topic of designing space-making robots, which are robotic envelopes and volumes (robotic walls, ceilings, floors, partitions, building skins, vehicle interiors, etc.) that define and reconfigure architectural spaces. Space-making robots are essential parts of smart built environment (SBE), architectural robotics, and smart city. They create, define, and reconfigure the architectural spaces we live in. Informed by HAI (Human Agent Interaction) and HRI (Human Robot Interaction) literature, the author argues that people have the tendency to perceive adaptive and interactive space-making robots as agents, so that they can be designed as our companions, partners, friends, etc. Consequently, the human-robot interactions of space-making robots can be designed as human-agent interactions. This design approach is proposed in this dissertation as the “HAI-based design paradigm for space-making robots,” which is validated through both theoretical lens and empirical studies. Based on this design paradigm, the author then proposes a patterned-based, design framework for collaborative environments as an exemplary application of this design paradigm, which is then validated qualitatively through a design exemplar of a partner-like, collaborative space-making robot. Since “space-making robots” are becoming

more and more prevalent in our lives especially in confined spaces, the proposed design paradigm and framework can be widely applied to the design of SBE, architectural robotics, and smart cities.

BIOGRAPHICAL SKETCH

Yixiao Wang is a human-centered designer and researcher who applies his interests in human-centered design, engineering, and the evaluation of robotic architecture and smart built environments. After graduating from Hunan University in China with a Bachelor of Architecture, he came to University of California, Berkeley (UC Berkeley) in the US for his master's degree in Architecture, focusing on digital architecture and new materials. His master's thesis won the Berkeley Thesis Award, "The KMD Prize of Design Excellence in Digital Architecture." After his graduation, he went to work for the Adam Sokol Architecture Practice as an intern for three months, and then continued his internship with Marc Fornes & Theverymany in Brooklyn, NY. for six months until he became a contract designer. He then stepped back from his professional architect career as he saw an opportunity to explore robotic architecture at the lab of CUIMSE (Clemson University Intelligent Material, Science & Engineering). He then spent one year and a half at the Clemson School of Architecture as a PhD student, and subsequently applied to the PhD program of Human Behavior and Design in the Department of DEA (Design and Environmental Analysis) at Cornell University. This program focuses on conducting human-centered research (e.g., research on human behavior, environmental psychology, human development, etc.) and then applying the results to the design process. During his PhD studies, he also completed a minor in Computer Science focusing on Artificial Intelligence, and a minor in Information Science focusing on Human-Computer Interaction. Yixiao Wang is currently applying his knowledge of research, design, and engineering in the fields of Smart Built Environment, Human-Robot/Human-Computer Interaction, and the Internet of Things.

To dad, who just retired from his 38th year of teaching at universities,
and who forever reminds me what it means to be a good teacher and mentor.
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CHAPTER I

INTRODUCTION

I. BACKGROUND: HOW DO WE LIVE BETTER IN SMALL SPACES?

The world population has been constantly growing throughout the modern history [1]. In the future we can foresee, there will be more of us on this planet. In many large cities around the world such as Singapore, New York, and Hong Kong (just to name a few), people are already living in very small spaces [2],[3],[4]. Given the current Covid-19 pandemic scenario, many people around the world are living, working, and entertaining themselves at home. For instance, about 42% of American workers are working from home and this working-from-home economy is "likely to continue long past the coronavirus pandemic that spawned it" [5]. Thus, there is an urgent need to develop new technologies that can reconfigure small interior spaces to support different living, working, leisure, and other human activities within one space.

At the same time, promising research opportunities are emerging for autonomous vehicles and space explorations. At the very frontier of self-driving technologies, many large companies such as Tesla, Google, Voyage, and Swift Navigation (just to name a few) are making good progresses. Waymo (a branch of Google) is already testing its fully autonomous vehicles across multiple locations in the U.S. where the vehicle drives every day in different types of real-world conditions [6]. At the frontier of space explorations, NASA is developing reusable Human Landing System to commute astronauts to the Moon starting from 2024 [7]. A few Americans may make the longest commute yet: to Mars, which will take more than six months one-way [7]. If fully autonomous (“Level 5” [8],[9]) vehicles free passengers from the chore of driving, and if a trip to Mars dedicates more than a year of a life to similarly tight spatial confines, there is an opportunity to make the compact environments inside vehicles the workplace of the future. Evidence shows that workplace environments impact the ability, productivity, and quality of life of workers as well as employer earnings [10],[11],[12]. Thus, developing technologies that can reconfigure compact vehicle interior spaces to support different work activities and improve working experiences are promising research directions with great social impact.

In addition, the world population is aging [13]. According to the “Why Population Aging Matters” report from NIH, family structures have been transformed by population aging, leaving senior citizens in short of support from family, friends, and professional caretakers [13]. The current healthcare systems “are shown to be inefficient and high-cost” in face of the rapid population aging today so that creative and innovative solutions are needed [14]. Smart interior spaces such as smart homes and nursing homes are becoming very promising technological innovations and research directions addressing the population aging problems both from societal and individual levels [15].

For all the cases mentioned above (e.g., small houses, autonomous vehicles, space capsules, smart homes, and smart nursing homes), the living, working, and learning experiences of the inhabitants can be made better – more easy, more productive, more fun – in spaces that are made reconfigurable, interactive, and adaptive by **Space-Making Robots.**

II. WHAT IS A SPACE-MAKING ROBOT?

Space-making robots, characterized as architectural, reconfigurable, and interactive, have emerged beginning in the late 1990s. Some of these are AI-embedded or perceived as intelligent, while others are not. Here, briefly, the author illustrates four design exemplars of space-making robots. (Figure 1): HypoSurface, MuscleBody, The Animated Work Environment, and the Interactive Wall.

HypoSurface (Goulthorpe, MIT, 2003)

"HypoSurface" is an interactive, electromagnet-actuated screen-wall that physically responds to sound, internet feeds, and human physical gestures [16]. It is highly flexible and responsive because each single "physical pixel" on the screen-wall is independently controlled by electromagnets. It can form organic shapes and generate dynamic reconfigurations when interacting with human users.

MuscleBody (Hyperbody Group, TU Delft, 2005)

"MuscleBody" is a playful, bulbous, interactive volume that can accommodate several inhabitants who, by their actions, cause the transformation of its shape, transparency, and sound [17]. It does not have an explicit architectural purpose for a target population and its reconfigurations are not well-defined or precisely controlled; however, it has the advantage of being a soft body which enables intimate and playful human-robot interactions.

The Animated Work Environment or "AWE" (Green, Clemson University, 2007)

"Animated Work Environment" is a robotic work environment—a robotic display wall and mobile worksurface—that reconfigures to support changing work needs based on user activity and preference [18]. AWE is partially intelligent because of its learning abilities and is distinguished by realizing more of the ambition of a robot one could live in: it precisely configures an architectural space designed to purposefully support human activity (working life).


HypoSurface (Goulthorpe, MIT, 2003)
MuscleBody (Hyperbody Group, TU Delft, 2005)
Animated Work Environment (Green, Clemson University, 2007)
InteractiveWall (Hyperbody Group, TU Delft, 2009)

Figure 1. Space-making Robot Exemplars

InteractiveWall (Hyperbody Group, TU Delft, 2009)

"InteractiveWall" is an interactive wall designed following the concept of "Emotive Architecture" whereby the wall reflects people's physical presence, in real-time, via movement of mass, lighting, and projections [19]. Compared with "HypoSurface," it has many fewer degrees of freedom since its limited number of reconfigurations are already built within its mechanical mechanism and physical limitations. However, covered with the high-tech stretchable fabric, its movements and interactions appear to be very elegant and well-defined.

A. Defining Space-Making Robots

The robots represented by the four exemplars above share the following characteristics:

1) They are physically far larger and more imposing than a person.
2) They are not objects in the environment as much as they shape the environment.
3) They, as space defining, providing novel affordances (e.g. altering the atmosphere of the space; giving form to human activity); and,
4) They are interactive and may be intelligent (or perceived as such).

In this dissertation, the author defines and will refer to these kinds of robots as "Space-Making Robots" – robots that define, reconfigure, and/or are embedded in existing physical environments. Figure 2 shows how the continuum robot surfaces as an exemplar of space-making robots. They can reconfigure a micro-office to support different working activities: "Individual Working" (picture on the left) and "Group Meeting" (picture on the right).

Figure 2. Space-Making Robot Surfaces Reconfiguring Compact Space for Individual Working (Left) and Group Meeting (Right).

B. Tendon-Driven Compliant Robot Surfaces

As shown in the examples in Figure 1 and Figure 2, most of the space-making robots are large-scale reconfigurable robot surfaces such as robotic walls, envelops, ceilings, etc. For the mechanical mechanism of space-making robots, this dissertation explores compliant robot surfaces featuring remote actuation of tendons embedded within the surface structure for the following three reasons:

1) 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 [20],[21],[22].
2) 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.
3) 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.

III. WHY SPACE-MAKING ROBOTS?

What can space-making robots do to address our needs, wants, and concerns related to small spaces? Here, the author discusses this question from the following five aspects of our everyday life: working, living, learning, and leisure.

A. Working: Reconfiguring Working Spaces

Space-making robots can reconfigure interior working spaces into many different spaces supporting many different activities at work. One example would be the “Animated Work Environment” which reconfigures the interior working spaces to support eight different activities: collaborating, composing, conference, gaming, lounging, playing, presenting, and viewing [18]. This reconfigurability of space-making robots addresses the small space issues in overcrowded large cities, autonomous vehicles, and space capsules where different work-related activities need to happen within one space.

B. Living: Facilitating Everyday Living

Space-making robots have also been applied to reconfigure one living space into many spaces. A good example would be the series of projects done by “Ori Living” [23], a pioneer robotic architecture company started by PhD students at MIT. In their projects, one bedroom can be reconfigured into a living room, a dining hall, a working space, etc. This application addresses the small space issues in overcrowded large cities, space capsules, and the current Covid-19 stay-at-home situation where the living space is also the space for working, learning, and leisure.

Moreover, space-making robots can also help people who are physically impaired and/or psychologically stressed to live an easier and better life. Exploratory research works in this area include the “SORT” swarm wall-climbing robots helping senior citizens to organize their things better [24] and “PheB” bio-robot surfaces helping with the regulation of breathing patterns to reduce people’s stress levels [25]. These explorative projects are shining light on the promising future where space-making robots can play important roles in smart homes and nursing homes helping the people in need, including senior citizens.

In addition, for the current situation of Covid-19 pandemic, space-making robot can reconfigure public spaces enabling safer and more efficient public environment. One example is shown in Figure 3 where the embedded soft robot surface can intelligently bend down to divide the space when people getting too close to each other.

Figure 3. Ceiling-Embedded Robot Surface Intelligently Separates the Crowd.

C. learning: Augmenting Learning Experiences

Space-making robots can also augment learning experiences by reconfiguring interior environments. One good example is "The LIT ROOM," which is an evocative, literacy support tool at room-scale [26]. "The LIT ROOM" reconfigures interior lighting and sound environments to simulate the atmospheres described in children's story books, so that the children can experience the "worlds" described in the "words" through multimedia environments. This example shows the application of space-making robots in education specifically for improving children's literacy.

D. Leisure: Creating Playful Experiences

Most of the space-making robot research projects from the architecture communities focus on the applications in recreation and leisure. Most of the space-making robot projects mentioned in Figure 1, including HypoSurface [16], MuscleBody [17], and InteractiveWall [19], are developed to create explorative and playful experiences. These examples show that space-making robots can be designed and engineered to be artistic and playful for interior spaces in different scales, including the compact spaces.

In summary, space-making robots have many important applications for current and future small spaces in our everyday life. Thus, as a design researcher, it is reasonable and desirable to ask the question: *How should we design space-making robots and their user interactions?* This is the research topic of this dissertation. Discussions on this topic will not only shape the design concept, approaches, and theories of space-making robots, but project a new design paradigm for smart built environments and even smart cities. First, let us look at where the concept "Space-Making Robot" is situated in current intellectual landscapes.

IV. LITERATURE REVIEW

A. Space-Making Robots, Architectural Robotics, SBE, and Smart City

Architecture has long been conceptualized as "a machine for living in" [27] in the words of Le Corbusier, a century ago, and, more recently, as "a robot for living in"

[28] by William Mitchel. Thus, from the perspectives of architects, conceptualizing robotics-embedded architecture as space-making robots (robots that make spaces) is not unfamiliar.

As characterized by Keith Evan Green, “architectural robotics” are “interactive, partly intelligent (may or may not be intelligent), and meticulously designed physical environments” [29]. An emerging subfield in robotics and architectural design, 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” [30],[31]. Architectural robotics follows, moreover, from the concept of Christopher Alexander et al. of a “compressed pattern” room as elaborated in *A Pattern Language* [32], conceived for the built environment but since applied to cyber-human systems [33] and human-robot interaction [34].

Examples of architectural robotics include smart and mobile furnishings [35], reconfigurable work environments [18], reconfigurable vehicle interiors [36], and interactive read-aloud spaces [37]. Some of these are space-making robots [18],[36],[37] and some of them are not [35]; some of these are intelligent [18],[35],[36] and some are not [37]. In any case, people may perceive intelligence in a robot that is without AI as human-agent interactions unfold [29],[30].

“Smart Built Environment” (SBE) is a concept that has been widely used but not clearly defined [38],[39],[40]. According to a comprehensive review of smart cities and smart spaces covering more than 100 articles, “Smart” is “a state of intelligence as applied to technologies and implementable solutions in relation to optimized performance levels without compromising sustainability and community (human) related aspects," and "Built Environment" is defined as "a material, spatial and cultural product of human labor that combines physical elements and energy in forms for living, working, and playing" [40]. Kumar and Mani define "Smart Built Environment" as "spaces integrated with sensors, actuator systems and intelligent control algorithms" [41]. The concepts given by the comprehensive review are very broad, while the definition from Kumar and Mani is very specific. However, these concepts all share the same emphasis on embedded intelligence and the physical elements of an environment. In this dissertation, the author defines SBEs as physical environments with sensor actuator systems and intelligent control algorithms. Both SBE and "Architectural Robotics" encompass physical elements of an environment, but SBE has to be intelligent (AI-embedded). "Space-making Robots" only refers to the physical elements that are more of spatial envelopes and volumes than objects in the environment; for Space-Making Robots, its physical elements do not have to be intelligent (AI-embedded). Figure 4 is a diagram showing the relationships between these concepts.

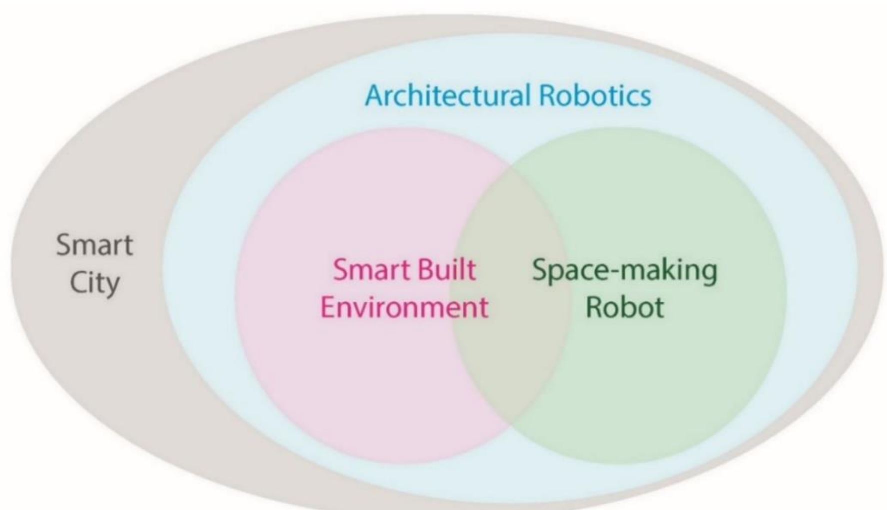

Figure 4. Concept Diagram of Smart City, Architectural Robotics, SBE, & Space-making Robot.

B. Space-Making Robots, Non-Humanoids, and Human Robot Interaction (HRI)

A Non-humanoid is a robot whose appearance does not resemble a human. Non-humanoid robots have been extensively investigated by HRI communities as "socially interactive robots": robots for which social human–robot interaction is important [42]. For example, the lamp robot "Kip1" [43], with a "head" and a "torso," is designed as a conversational companion that reacts to the volume of the human voice through its movements as if it understands the context of human conversational exchanges. If people speak too loudly, Kip1 will shrink rapidly and tremble constantly as if it is in fear. Its behavior raises people's compassion and their awareness of their voice volume in conversations. Another example, the mobile, robotic "mechanical ottoman" [44] exhibits carefully designed movements that encourage people to use it to support their legs or as a stool. Its movements also evoke users' perceptions that this "mechanical ottoman" is not only alive (running around as if a pet), but also polite by pausing at a distance before further approaching the users. There are other examples where non-humanoid robots and their interactions with users are designed as social actors and social interactions, such as the "Automatic Door" [45], "Marimba-Playing Robot Head" [46], and "Robotic Speaker Dock" [46].

Typologically, space-making robots are nonhumanoid and yet distinct from many nonhumanoid robots developed and studied by the HRI community, in three respects. Firstly, many of the nonhumanoid robots of HRI research are, to a degree, made to look anthropomorphic (e.g., "Kip1" [43] mentioned above), whereas space-making robots are not. Secondly, many of the nonhumanoid robots of HRI research are mobile (e.g., the "mechanical ottoman" robot [44] mentioned above), whereas space-making robots are not. Thirdly, most of the non-humanoid robots of HRI research are objects [46], while space-making robots are integral to the physical environment (i.e. embedded). These differences may greatly influence users' perception of space-making robots [44],[46],[47]. In HRI research, very few studies have been conducted to investigate robots that are not anthropomorphic, not mobile, and yet capable of reconfiguring the physical environment as do space-making robots [46].

C. Human Agent Interaction (HAI)

The research paradigm, Human Agent Interaction (HAI), is well established in design research, both as a theoretical foundation (e.g. [48],[49]) and in informing empirical studies (e.g. [43],[44]) in both the HCI and HRI communities [42]. Core to the HAI paradigm is its definition of "agent." Through this theoretical lens, in the context of HCI research, Norman emphasizes that an "agent" is defined as both social and intelligent [48], and Cassell defines "agent" as an interface or, more broadly, a computational system perceived as a person [49]. Similarly, Osawa and Imai argues that a system is only an "agent" when it is perceived as one (i.e. an "agent," perceived by users as an artificial, social actor) [50]. From HRI research, Wendy Ju et al. use the constructs of "perceived recognition" and "perceived intention" to measure if a nonhumanoid robot is considered "alive" by users [44].

In this dissertation, the author borrows, in particular, the definition of "agent" from Osawa and Imai: an "agent" defined as "an artificial social actor that is accepted by users through his/her intentional stance based on Dennett's Intentional Stance [51], "whether users are conscious or unconscious of the fact" [50]. The authors employed this particular definition of "agent" because this definition encompasses the key elements that define agency as proposed in literature [42],[44],[48],[49],[51]. According to this definition, "agent" encompasses the concepts of "Intentional System" (based on Dennett's Intentional Stance [51]), "Intelligent Agent" [52],[53], and "Social Actor" [54],[55],[56]. To lay a solid foundation for further discussions, these three concepts are further explained as below:

"Intentional System" is an entity "whose behavior can be predicted by the method of attributing *beliefs, desires,* and *rational acumen*" to the system according to the following three principles: "A system's beliefs are those it ought to have, given its perceptual capacities, its epistemic needs, and its biography," "A system's desires are those it ought to have, given its biological needs and the most practicable means of satisfying them," and "A system's behavior will consist of those acts that it would be rational for an agent with those beliefs and desires to perform" [51]. In summary, "Intentional System" is perceived by people as an entity that has belief, desire, and rationality so that its behavior and action are predictable. Dennett also constantly refers to "Intentional System" as "Rational Agent" in his article [51], and the mental representation of "Intentional System" is the "Intentional Stance."

"Intelligent Agent" refers to an autonomous entity that has goals and act to achieve its goals based on its understanding of the environment and capability to perform actions [52],[53]. An intelligent agent can be very complex or very simple. A humanoid robot capable of talking with people is an "intelligent agent," and an old-fashioned thermometer capable of measuring room temperature to control the heating system is also an "intelligent agent" [53]. Please be noted that the concept of "Intelligent

Agent" is totally based on the capability of the system, not people's perception of these system capabilities.

"Social Actors" are entities "who engages in intentional action which is shaped by internalized expectations about how others will interpret its meaning" [54], and according to Max Weber's social action theory [55], the "intentional action" here is what he defined as "social action." A pair of social actions become "social contacts," which is the beginning of "social interaction" [56]. Repeated and regular "social interactions" will generate "social relations" [56]. "Social Actor" describes the concept of "Agent" through its social actions towards and interactions with other agents in a society of robot or human.

Thus, to be more specific, *the "Agent" in this dissertation is an entity (or an artificial actor) that is perceived as an "Intelligent Agent" and a "Social Actor" through user's intentional stance.*

V. AN HAI-BASED DESIGN PARADIGM FOR SPACE-MAKING ROBOTS

Now, let us return to the research topic: How should we design space-making robots and their user interactions? As the author just mentioned, space-making robots are typologically non-humanoid robots; and non-humanoid robots can be designed, engineered, and evaluated as "socially interactive robots." Thus, it is plausible to ask the question: *Can space-making robots be designed as "socially interactive robots"?* Since there are significant differences between "space-making robots" and the non-humanoid robots having been investigated by HRI communities, this is a question yet to be answered. However, if people do perceive space-making robots as "agents" ("intelligent agents" and "social actors" in people's "intentional stance," as defined in section VI) in the same way as common non-humanoid robots can be perceived [43],[44],[45],[46], it would then make sense to design space-making robots as socially interactive robots and their user interactions as human-agent interactions.

Thus, the key question here is this: do people perceive space-making robots as "agents"? In this dissertation, the author discusses this question both through theoretical lenses (e.g., communication theories [57].) and empirical studies with both qualitative and quantitative approaches [58]. The results indicate that people do perceive intelligence, recognition, intention, friendliness, cooperativeness, collaboration, and welcome from the carefully designed space-making robot behavior, which strongly suggest that space-making robots can be perceived as agents. *Thus, space-making robots can be designed to evoke people's agency perception of them, and their user interactions can be designed as human-agent interactions.* This is the "HAI-based design paradigm for space-making robots" proposed by the author. A vision of this design paradigm is illustrated in Appendix A1, animation: A Room Alive. Please be noted that this design paradigm is based on users' agency perception: when I say "a space-making robot is designed as an agent," it means that the space-making robot is designed to be perceived by users as an agent. This agent can be human-like (sharing some characteristics with human), pet-like, partner-like, companion-like, etc. as long as it satisfies the definition of "agent" in this dissertation. Thus, an artificial system that has no AI but somehow, evokes users' agency perception, can also be designed as an agent under this paradigm.

To apply this design paradigm rigorously in the design process, the author proposed a "pattern-based, design framework for collaborative environment" as an exemplary design framework under the HAI-based design paradigm. This design framework was qualitatively validated through a design exemplar of "pattern-based, collaborative working environment" informed by observational partnership studies [57].

VI. DISSERTATION OVERVIEW

The main contents of this dissertation unfold in four sections:

First, based on the existed literature of non-humanoid robots, the author proposed the assumption that people can perceive space-making robots as agents since space-making robots are typologically, non-humanoid robots. Based on this assumption, the author then proposed a design-research framework for space-making robots [57]. This design framework consists of three steps: 1) Conduct ethnographic study of human design partners' interactions through non-participant observation; 2) Code observation results into human-human interaction patterns through grounded theory coding techniques; 3) Map human-human interaction patterns into human-"space-making robot" interaction patterns through three of the author's concepts: "direct mapping," "conveyed mapping," and "space agency" [57]. A design exemplar of a partner-like, collaborative space-making robot is then presented as a design validation of the proposed design-research framework.

Second, the assumption upon which the design paradigm and framework are proposed is a deduction from the research work on non-humanoid robots whose embodiment, scale, mobility, and other inherent characteristics are very different from space-making robots. Thus, further validation of this assumption is needed. To validate this assumption, the author needs to investigate users' perception of space-making robots whose configurations, movements, and form factors should be meticulously designed and controlled for user experiments. Thus, the author developed two space-making robots which are compliant and tendon-driven. In this dissertation, the author presented the design, engineering, and evaluation of the two space-making continuum robot surfaces with different mechanisms: one for building-scale applications [59] and one for interior scale applications [60].

Third, using the interior-scale space-making robot, the author conducted three user studies to 1) eliminate key usability issues of this space-making robot for the experiment scenario; 2) probe users' interactions with and perceptions of the space-making robot through a qualitative in-lab experiment; 3) investigate users' perception of the space-making robot through both qualitative and quantitative online experiments. Both the qualitative and quantitative experiment results strongly suggest that users do perceive agency (intelligence, recognition, intention, friendliness, welcome, collaboration, and cooperation) through the dynamic, autonomous, and designed movements of the robot surface [58]. These studies serve as the empirical validation of the assumption proposed in section one.

Finally, a qualitative in-lab user study is presented to investigate the user preference for different interaction modes (Button, Voice Control, Human Activity Recognition, Natural Language Processing, Graphic User Interface, and Proximity Sensor) in different working tasks and scenarios when users working together with the partner-like space-making robot (the robot surface) in a compact office. This study provides valuable empirical data unveiling why users prefer certain interaction modes when working together with a partner-like space-making robots.

VII. DISSERTATION STRUCTURE, CHAPTER BY CHAPTER

Research Topic: How should we design space-making robots and their user interactions? (CHAPTER I)

Research Question 1: Will space-making robots be perceived as agents? (CHAPTER I)

Research Question 2: If space-making robots are agents, how can this user perception be applied as a design concept rigorously through the design process? (CHAPTER I)

Hypothesis 1: Users perceive space-making robots as agents (CHAPTER II).

Hypothesis 2: The "pattern-based, design framework for space-making robots" is one way to guide a rigorous design process for space-making robots (CHAPTER II).

Validation for Hypothesis 2: A design exemplar of "a partner-like, collaborative space-making robots" as a qualitative validation, informed by an observational user study. (CHAPTER II)

Developing Space-Making Robot Prototypes: Design, engineering, and evaluation of space-making continuum robot surfaces which will be used in empirical user studies for hypothesis validation (CHAPTER III & IV).

Validation for Hypothesis 1: Qualitative and quantitative experiments investigating if users will perceive a continuum robot surface as an agent through its designed, autonomous, and dynamic movement (CHAPTER V).

User Preferences for Different Interaction Modes: Investigating in which scenarios users prefer agent-like interactions with space-making robots, and why (CHAPTER VI).

Conclusion: conclusions for each chapter and the whole dissertation. (CHAPTER VII).

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CHAPTER II

A PATTERN-BASED, DESIGN FRAMEWORK FOR DESIGNING SPACE-MAKING ROBOTS

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ABSTRACT

HAI (Human Agent Interaction) and HRI (Human Robot Interaction) literatures suggest that people tend to interact with interactive artifacts as if these were human. For decades, this understanding has been applied to designing singular, embedded artifacts at a small physical scale. In this chapter, the author extends the same theory and practice to the dimension of space—to designing interactive, physical environments and space-making robots (defined in Chapter I). When space-making robots are designed as agents, their interactions with human users are designed as Human-Agent Interactions (HAI). Thus, the author proposed the HAI-based design paradigm for space-making robots. A conceptual ground for this is found in a "pattern language" developed by Alexander et al. for designing static physical environments. Upon this ground, the author constructed a systematic framework for designing collaborative (or partner-like) space-making robots shaped, as well, by my own concepts, Direct Mapping, Conveyed Mapping, and Space Agency, to strive for more partner-like interactions between human beings and their physical surroundings. The ethnographic study in this chapter generates a hypothetical design as a qualitative validation of the framework, which has significance for designing tangible, embedded, and embodied interaction as it extends, inevitably, to the dimension of space, entertaining, serving, and augmenting us.

I. INTRODUCTION

A Pattern Language (1977) [1] by Alexander, Ishikawa, and Silverstein was highly influential in architecture but has since become more impactful on computer science and its allied disciplines (as reviewed by [2]). A Pattern Language is comprised of 253 patterns guiding environmental design, presented as drawn diagrams and written narratives which "represent our best guess as to what arrangement…will work to solve…a problem which occurs over and over again" [1]. For instance, pattern 185, "Sitting Circle" (figure 1), offers an arrangement of living room furniture, whereby the selection of furnishings and their placement, relative to the walls defining the room, allow for an intimate correspondence between those who are seated as well as a path for others to circumvent this intimate gathering with the least disruption and most efficient movement. Recognize that pattern 185, typical of A Pattern Language, was as much about how people interact with each other—how they collaborate—as how people interact with their physical surroundings. Patterns were meant to be assembled into familiar routines of people and places that define our everyday lives.

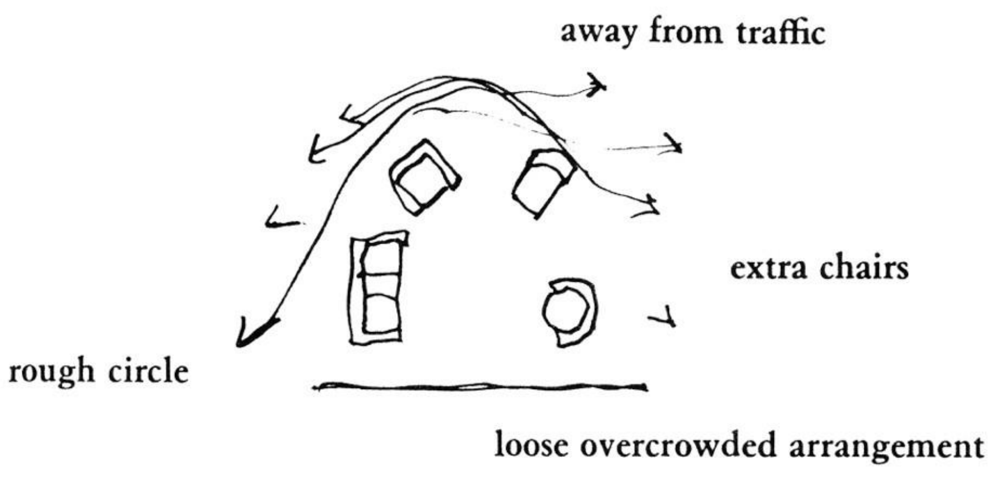


Figure 1. Pattern number 185, "Sitting Circle" [1].

In computer science and its allied disciplines, a pattern-based framework has been applied to the design of software (e.g. “reusable object-oriented software” [3]) and to computer games (e.g. [4]; and to the expanding realm of IoT [5]). The author believes that a networked suite of interactive devices is inherently spatial as compared to human-computer interaction with a singular device, which is 1 to 1. A pattern-based framework has also been impactful in social and assistive robot research (see [6] for an overview), where it informs robot-environment interaction and also robot-human interaction whereby the robot exhibits human-like “behavioral patterns” perceived by humans as approachable, familiar, or what defined here as “collaborative.” As will be explored later in this paper, a pattern-based framework may also prove productive to the emerging domain of interactive and intelligent environments first imagined, tellingly, by a circle of researchers to which Alexander belonged that included Nicholas Negroponte (as elaborated in “Soft Architecture Machines” [7]) and Gordan Pask (in “The Architectural Relevance of Cybernetics” [8]).

But the pattern language of Alexander et al., being based on professional “best guesses” [1] and conceived for designing static environments, is arguably an inadequate framework for designing computational systems that are spatial, collaborative, or both, given the complex interactions such systems afford. Consequently, this chapter posits the question: what is a pattern-based framework for designing computational artifacts that are integral to or constitute a collaborative environment? In my effort to respond, the author recognizes such architectural, spatial, and adaptive artifacts as “agents” [9] (defined in Chapter I), that is aware of, transmits, and receives information from the world, and also manipulates aspects of the world.

Sequence	Research Activity	Interactive System	The "Lens" Used
1st	Ethnographic Study	Human-Human	Observation
2nd	Coding of Interaction Patterns	Human-Human	*From the literature:* • Grounded Theory Coding • Design Partnerships • Joint Action • CSCW Creative Workplace
3rd	Coding of Interaction Patterns	Human-Collaborative Environment	*Our own:* • Direct Mapping • Conveyed Mapping • Space Agency

Table 1. The design-research framework based on studies, theories, and other literatures.

Rather than a framework drawn from "best guesses," this pattern-based framework overviewed in Table 1 is: (a) based in ethnography, (b) informed by a consideration of the literature (especially, HRI and HAI), and (c) shaped by three of the author's own concepts—Direct Mapping, Conveyed Mapping, and Space Agency. Later in this paper, as a means to validate this framework, the author reports on an ethnographic study that sought patterns in human-human interaction that the author translated into patterns of interaction between humans and a space-making robot of the author's own design. This singular case suggests an early, qualitative validation of the framework. The author envisions, in the future, this framework informs the design of wide-ranging tangible, embedded, and embodied artifacts as these become increasingly collaborative with us and extend, inevitably, to the dimension of space—supporting, entertaining, and augmenting us.

II. THEORETICAL FOUNDATIONS

In developing my pattern-based framework, I drew inspiration from the literature of Human-Robot Interaction (HRI), particularly the literature of non-humanoid robots perceived and also treated by human as something recognizant, intentional, and intelligent [18],[19],[20]. Robotics-embedded interactive environments are computer-embedded media that do not look like a human figure. Thus, arguably, interactive environments may also be perceived by users as social actors, whose interaction with users will then become "Human Agent Interactions" (HAI) [15]. Thus, the author proposes the HAI-based design paradigm where adaptive, space-making robots are designed as "agents" and human- "space-making robot" interactions are designed as human-agent interactions. The works from HRI and HAI are considered as the foundations for this pattern-based, design framework for space-making robots.

A Brief Review of HRI and HAI (for details, please refer to Chapter I)

Many psychological experiments studying human communications have informed human-computer interaction design [16]. Initially, design researchers applied these psychological findings to virtual, avatar designs [17]. More recently, design researchers have been transferring "common, interpersonal communication phenomena" [16],[11] to tangible, embedded, and embodied systems such as social robots [18],[19], and robotic furniture [20] (the latter being pertinent to our case study, presented later in this paper). As will be elaborated here, I extend this conceptualization to a robotics-embedded collaborative environment supporting and potentially augmenting work activity. In my proposed design framework, studying human-human collaboration reveals patterns of interactions that translate to patterns of how people and a space-making robot might interact. Such patterns could then shape how collaborative environments and their components are designed, and the interactions such agents afford.

III. ANALYTICAL FOUNDATIONS

In developing our pattern-based framework, the author also drew inspiration from four analytical foundations from the literature: the grounded theory coding method, and the literature of design partnerships, Joint Action, and Creative Workplaces drawn from the CSCW (Computer-Supported Cooperative Work) community. the author briefly considered these foundations and their import to the framework.

A. Grounded Theory Coding Method

"Grounded theory coding method" [21] is a well-accepted and commonly used coding technique for analyzing transcripts of ethnographic studies [22]. Charmaz identifies four steps [21] in the grounded theory coding process: "initial coding," "focused coding," "axle coding," and "theoretical coding." At a minimum, grounded theory coding should include "initial coding" and "focused coding" (as my research team accomplished in the "Design Validation," soon to be considered). There are several reasons to use grounded theory coding method in a pattern-based design framework; the most important one is that grounded theory coding requires researchers to "stop and ask analytic questions" of the data collected [21]. Such questions not only "further our understandings to the studied life," but also "help us direct subsequent data-gathering toward the analytic issues we are defining" [21]. In this way, design researchers are not only identifying interaction patterns, but also exploring deeper questions such as the why and how certain interactions occur. Asking these questions is vital for deeply understanding human-human interaction that lends well to coding robust, human-"space-making robot" interaction patterns.

B. Design Partnerships, Joint Action, and CSCW

In developing this framework, the author attended to a review of the literature pertaining to how design partners "design-think" [23],[24],[25] and both gesture and communicate through design, with special consideration of "face-to-face gestural interactions" occurring during the design process [26]. Insights from this literature inform the ethnographic study of human-human collaboration, offering sign-posts to the activity of observation. From the psychology literature (e.g. [27]), interactions between human beings working closely together may be categorized as "joint actions," which describes both "emergent coordination" and "planned coordination." People perform "joint actions" when they "coordinate their actions in space and time to produce a joint outcome" [27]. When two people work together (as we observed in our case study of collaborating, human designers), the collaborating couple or group performs "joint actions" with clear goals and purposes, a "coordination" pattern of human-human actions characterized as "planned." Human-human coordination may also "emerge," unplanned [27]. Furthermore, our framework was informed by the literature from "design communication" (e.g. [28]) and CSCW. The author found particular relevance in CSCW research focusing on Creative Workplaces [29],[30] with a focus on empirical studies recording sequences and frequencies of different design activities [28] and properties of "work space informal communications" such as "frequency, duration, and whether [such communications are] pre-arranged" [30]. These studies inspired us to further investigate how social cues "shape task coordination and communication" [29].

C. Creative Workplaces

Towards conceptualizing our framework, the author also found inspiration in empirical studies focused on physical settings salient to creativity in the workplace. Martens [31] outlined typical characteristics of the creative office: it is "informal," "family like," and provides a degree of user "control over the space." Furthermore, McCoy and Evans [32] identify five abstract dimensions of the creative workspace: "nature," "challenge," "freedom," "support," and "coherence." For each of these, McCoy and Evans elaborated its formal characteristics: "spatial form (size, dimension & shape)," "light," "internal organization of objects," "characteristics of bounding surface," "color," "texture," and so on. [32]. Stokols et al. [33] meanwhile argue that "levels of environmental distraction (noise, foot traffic, etc.)" are significantly related to "perceived support for creativity at work" [33]. Additionally, Martens [31] and McCoy [32],[34] performed literature reviews on "physical workspaces" and "creativity" that suggest that creative workplaces offer a variety of personalized spaces, secluded private spaces (offering "freedom, security and control") and "open offices" [31]. The Creative Workplaces findings and characterizations were helpful to us in forming an understanding of the physical context that shapes the collaboration of human partners.

What might seem a haphazard encounter with various literature has, taken together, significant implications for understanding human-human partnerships as afforded by the physical environment, and especially those environments created by "Space-Making Robots" which are interactive and moreover "collaborative."

IV. THREE NEW "TRANSLATIONAL" CONCEPTS

Designing space-making robots that is perceived as human-like, or what the author calls here "collaborative," brings new design challenges. In designing a collaborative space-making robots, the designer transfers observable human-human interaction patterns as much as, and as precisely as possible, to human-environment interactions so that users interact with their physical surroundings as if the environment and its component parts were human-like in at least some respects. Towards this aspiration, the author introduces three novel concepts to guide the design process of mapping human-human interaction patterns to human-"space-making robot" interaction patterns.

A. Direct Mapping

In the proposed design framework (as captured in Table 1), observations of human-human interaction are coded as patterns—a coding procedure that is not trivial but also not unfamiliar to many design researchers. Subsequently, such human-human interaction patterns are translated into human- "space-making robot" interaction patterns. This translation is very much itself a design process—part-science, part-art. Some human-human interaction patterns can be "directly mapped" to human- "space-making robot" interaction patterns. For instance, people actively engaged in collaboration with one another frequently use their arms to form gestures that communicate their ideas. In direct mapping, these physical gestures formed by human arms are recreated rather directly in the cyber-physical system.

The author uses the term "Direct Mapping," thus, to describe a design process in which human-human interaction patterns are directly copied, imitated, and applied to human-“space-making robot” interaction designs. For instance, a robotic arm might closely replicate the gestures observed in the human-human workspace. Presumably, the same gestures enacted by strips of robot surfaces would convey the same messages to a collaborating human as did the human arm. This presumption has already been verified in human-robot interaction research [18],[35],[36], and [37] where Direct Mapping predominates. For example, Hoffman et al. designed a lamp robot called “Kip” [35] that directly maps various human expressions of fear, curiosity, and calm. Another example focused on the built environment, comes from Ju et al. [36], whereby an automatic door “gestures” those entering a building as if it were a doorman opening the door.

B. Conveyed Mapping

There are many human-human interaction patterns that cannot be directly mapped to human-environment interactions. Obvious examples include eye contact, facial expressions, a sense of humor, and other subtle gestures. It is indeed difficult to imagine how a space-making robot (such as a robotic wall), no matter how interactive or intelligent, could offer “eye contact” “smile,” or “wink” to its human collaborators. Many of these subtle but significant social cues are used for reaching a common ground amongst human collaborators, during verbal communication, as defined and studied in the theory of “Grounding in Communication” [38]. Although these communications cannot be directly mapped to, say, a smart device, the meaning of these communications delivered by such a device—the messages it conveys—can be understood by human recipients. Consequently, the author strives to design human-machine interactions in which the artifact conveys sufficient (i.e. discernable, perceivable) approximations of cues that humans naturally convey using subtle, social cues. For example, although a space-making robot cannot “nod its head” to encourage a conversation, maybe it can “blink” green LED lights during a conversation to convey a semblance of encouragement to a human partner. The author therefore uses the term Conveyed Mapping to describe a design process in which human-human interaction patterns cannot be directly mapped to an artifact but nevertheless can be mapped in such a way as to convey the same core message as found in human-human interactions. The conveyance comes by way of a substituted gesture that the system is designed to deliver (e.g. approval by “green blinking lights” as a conveyance of “head nodding”).

C. Space Agency

In recent years, HCI research has, on one hand, focused on designing objects that might take a more figurative form (e.g. the aforementioned “Kip” [36]) or a more abstract form (e.g. a “mechanical ottoman” [37]) that is, in both cases, perceived by users as human-like. On the other hand, HCI research has increasingly focused on the dimension of space, extending “ubiquitous computing” to (for one) “smart cities” with special attention to “natural interfaces, context-aware applications, and automated capture and access” [39]. These two tendencies of HCI suggest the importance of human-like agency and “cyberspace” [40] that, taken together, suggest the need of HCI designers to focus attention increasingly on realizing an “information space” [41], one that seems familiar, or (at least) one that invites collaboration. However, HCI researchers entering this research domain have tended to focus more on embedding technologies into existing infrastructure rather than designing newly realized, cyber-human environments [39]. The author calls the latter a “Space Agent” (see figure 2) an interactive or intelligent artifact that is both environmental (i.e. space-making) and human-like in (at least some of) its behavior. Situated in HCI's intellectual landscape somewhere in the space between smart objects, intelligent environments, and smart cities, Space Agents are capable of performing some manipulation tasks we might expect from a humanoid or industrial robot (e.g. grasping, reaching, supporting, pointing, twisting, carrying, pushing, lifting) while also capable of reconfiguring the spatial envelope of the room to shape, essentially, "different rooms" matched to the unfolding of human-"space-making robot" collaboration.

Figure 2. Our vision of how Space Agents (here, robot surfaces) might be implemented in a fully autonomous car.

The author uses the term "Space Agency," thus, to describe that design attribute in which human-human interaction patterns are embodied in a collaborative environment or its constituent components to forge productive and satisfying human-environment interactions.

V. DESIGN VALIDATION: A PARTNER-LIKE SPACE-MAKING ROBOT

The author used the proposed pattern-based framework, overviewed in Table 1 and elaborated in the previous sections, to design a space-making robot inspired by recent interactive and intelligent architectural robotics [2], including the InteractiveWall

[42] by the Hyperbody Research Group (TU Delft), Lift-Bit [34] by Carlo Ratti (MIT), AWE [2] by Keith Evan Green (Cornell), and the ambientROOM by Hiroshi Ishii (MIT) [40]. For this space-making robot (that reconfigure working spaces), the author envisioned a tendon-driven robot surface that is a cross between a human arm and a physically reconfigurable "ribbon" several feet in length (see figure 2). Performing manipulation tasks and defining the physical envelopes of rooms. As mentioned in Chapter I, space-making robots have potential, promising application to interiors of many kinds, including dwellings, hospitals, autonomous vehicles, spacecraft, and space habitation. Figure 2 shows our space-making robot surfaces implemented in a fully autonomous ("level-5") vehicle. The design objective is twofold: (a) to provide inhabitants many "rooms" configured by these robotic surfaces within a relatively compact habitable space; and (b) to envision such robotic surfaces not as components of a passive frame but as intelligent agents partnering with their inhabitants performing creative tasks.

The author began the design cycle by observing human pairs partnering on a design task. From these observations, the author generated patterns modeling human-human interactions which then were translated to patterns of interaction for a human designer collaborating with an intelligent, "humanlike," physical space to accomplish the same design task. Interactions of human design partners were systematically coded as informed by Charmaz's "grounded theory coding technique" [21], design-partnership studies defined as "joint action" [27], and the CSCW literatures [30] (particularly that of the "Creative Workplace") [31]. Study results were mapped to human-environment interaction patterns guided by our three concepts introduced here for the first time: Direct Mapping, Conveyed Mapping, and Space Agency.

Focused Coding	**Initial Coding**	**Insights from Former Research & Theories**
Non-verbal, bodily communication	arm gestures; shape, direction & feelings; mimicking characters, etc.	Four types of gestures for design tasks and meetings: kinetic, spatial, pointing & other [5].
Inspiration cues	brain storming; abstract ideas; bold designs; share personal stories and experiences; ideas on drawing boards, etc.	Create idea maps and leverage ideas from others to generate more creative and diverse ideas [6].
Facial expressions, eye contact, social cues.	eye contact with audience; showing interest and enthusiasm; positive confirmation; conversational encouragements, etc.	Four themes (with 13 models) for observed social cues and task outcomes; rapport in negotiation (laugh); establish procedural grounding (gaze); deictic in shared contexts gestures (points); non-verbal feedback to avoid interruptions (nod) [7].
Cheerful & relaxed atmosphere	funny pictures or news; smiling face stickers on walls; cheerful talks; chatting and gossip; snacks, etc.	"SYMLOG three-dimensional-space"—a positive working atmosphere encouraging creative discussions and improving work efficiency [8].
Place-based cues	Tell stories of a remote place: travelled there before; lived there before; having friends there; perception of the culture; local practices and policies, etc.	Using lights, sounds and movements to simulate environment, seasons, feelings of the places described in story books [9].

Table 2. Study results of the initial design partnership study – five examples.

A. Ethnographic Studies of Design Partnerships

This ethnographic study focused on understanding face-to-face interactions between design partners collaborating on a design task. In this study, the author observed four groups of designers (12 participants in total), each group comprised of two to four designers. The first three groups were formed by undergraduate design majors at Cornell University, while the fourth group had one professional architect and one design-focused doctoral student. Members of the three groups of undergraduate designers granted us permission to conduct observations of and interviews on their design processes, and to record field notes, pictures and videos. Members of the fourth group—the design professional and the Ph.D. student—only permitted us to conduct interviews with them. The author did a forty-minute in-depth interview with this one group. For each of the three undergraduate student groups, the author observed each group's design process in their studio workspaces for no less than 1.5 hours and as many as 3 hours, and recorded their interactions using video cameras, digital cameras, and hand-written field notes. At the end of each session, the author did a 15-minute interview with one member of each team.

Following the observations, the author coded the field notes and digital photos, and transcribed the video recordings [43], analyzing the transcribed materials using Charmaz's grounded theory coding techniques (i.e. "initial coding" and "focused coding") [21]. Given this chapter's focus on a design-research framework, the author presents here in Table 2 (found on the previous page) only the coding results and their associations with what were learned from the most relevant literatures.

B. Mapping Human-Human Interactions to Human-Environment Interactions

From the coding results and insights, the author identified four distinct human-human interaction patterns as a means to validate my design-research framework:

- *Arm Gestures* are a means of pointing and communicating shape, size, directionality, and other forms of communication produced by the upper limbs.
- *Positive Social* Cues express enthusiasm, encouragement, or agreement.
- *Inspirational Cues* include storytelling and sharing abstract ideas.
- *Place-based Cues* reference remote places, including their histories, cultures, local living styles, policies, etc.

Arm Gestures are interaction patterns involving physical movements of the arms. For Arm Gestures, the author used Direct Mapping, given that these physical gestures can be transferred directly to the physical trajectories of the space agents.

Positive Social Cues such as those communicating enthusiasm are difficult to directly map to the Space Agent. Thus, the author used Conveyed Mapping to convey the same messages by creating new forms of interaction that can be achieved via the Space Agents. For instance, a Space Agent might express enthusiasm through its animated movements and flashing rainbow colors produced by embedded LEDs.

Inspirational Cues are the stories and shared experiences people tell each other to get inspired. There are many ways a room might tell a story. Direct Mapping could, for instance, suggest having the room and human designer “exchange” stories with the use of a whiteboard: the human designer can use the whiteboard to post ideas, and the room’s intelligent system then uses this input to search the internet for relevant stories (news reports, documentaries, fictional accounts etc.) based on the keywords of the post.

This information can be presented on a display embedded in the Space Agent or on the wall or ceiling, and the Space Agent might move and emit color and audio to bring attention to the story and even capture the atmosphere of it (as our lab has done previously with the LIT ROOM [2]).

Place-based Cues might communicate information about a remote place that is relevant and informative to the work at hand. While the human designer may use only words and nonverbal communication such as hand gestures to describe a remote place, Indirect Mapping might make full use of the Space Agents with its embedded lighting and audio to evoke the site environment and its atmosphere, rendering the whole of the environment a "portal" to somewhere else [2]. This use of ambient media is partly inspired by Ishii's ambientROOM [40] cited earlier, which communicates information more in the background than the foreground of our attention. However, for this design exemplar, the author imagines ambient media also being, when appropriate, in the foreground of our attention, depending on the context.

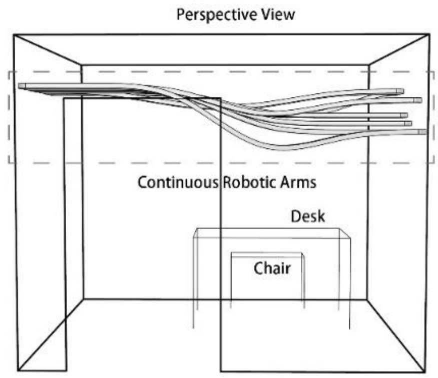
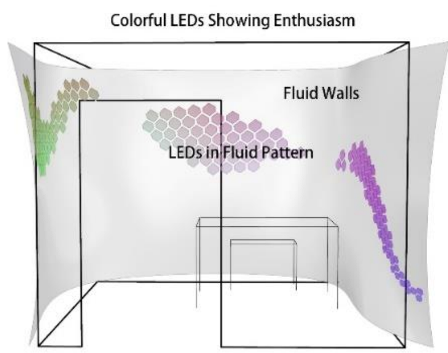
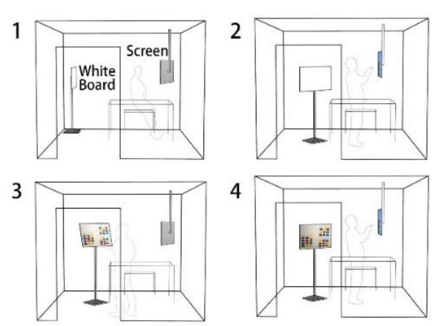
For this design exemplar (at least), a key contribution of the space-making robot surface is its capacity to bring an element of surprise to the creative process that, for Dorst [23] and Maher [25], offers that "impetus for framing and reframing the problem, thereby avoiding routine," [23] rather unproductive behavior in the designer.

In the design activity, one should recognize that the application of either Direct Mapping, Conveyed Mapping, or Indirect Mapping is a design decision made by design researchers. Similarly, even with the same mapping method, different designers might arrive at different design outcomes because of the creative nature of implementing the pattern-based framework. The three mapping strategies of our pattern-based framework—Direct and Conveyed Mapping, and Space Agency—are intended to generate inspired design solutions rather than rigid or formulaic outcomes.

C. From Human-Environment Interactions to Design Patterns

In this section, the author explores how the human-environment interaction patterns might generate "design patterns" for a collaborative environment supporting and even augmenting design activity. Helpful to us in this translation was the "Creative Workplace" literature, for instance, in suggesting the use of "fluid shapes" in space [34] for fostering creativity. As follows, the space-making robots (of continuum robot technology [2]) allow for fluid rather than rigid motion and shape-making. Additionally, following Martens' suggestion [31] that workspaces provide users with some measure of control over their physical environment, the author designed an environment that may be physically shaped by direct control of its human collaborators.

Table 3 illustrates the human- "space-making robot" interaction patterns and the corresponding design patterns generated. The author recognizes that these patterns are neither the only patterns nor the best design patterns. Nonetheless, these patterns are reasonable and logical ones based on the human-environment interaction patterns and what were drew from the Creative Workplace literature. In Table 3, the author present these patterns in the manner of A Pattern Language—as both diagrams and brief narratives.

<table>
<tr><th>Human-“Space-Making Robot” Interaction Patterns</th><th>Design Patterns Diagrams</th><th>Descriptions for Design Patterns</th></tr>
<tr><td>Arm Gestures
to
Space Agents</td><td>
</td><td>Space Agents (continuum robot surfaces) physically reconfigure to “point” and to convey shape, orientation, direction, and the like. These robot surfaces can be mounted on or embedded flush with ceiling and wall surfaces or, alternatively, be free-standing within the volume of the room.</td></tr>
<tr><td>Positive Social Cues
to
lighting effect</td><td>
</td><td>Lighting is one means to convey “positive social cues,” changes in color, intensity, patterning, and periodicity/duration may be perceived by the human collaborator as a form of encouragement. Such lighting may be combined with the movement of the Space Agents to further the impact.</td></tr>
<tr><td>Inspiration Cues (storytelling)
to
white board input by designer and responsive content identified by AI, presented on displays</td><td>
</td><td>The collaborative environment and human designer can “exchange” stories with use of a whiteboard: the human designer can use the whiteboard to post ideas, and the room’s intelligent system then uses this input to search the internet for relevant stories based on the keywords on the posts, which will be presented to users through various media.</td></tr>
</table>

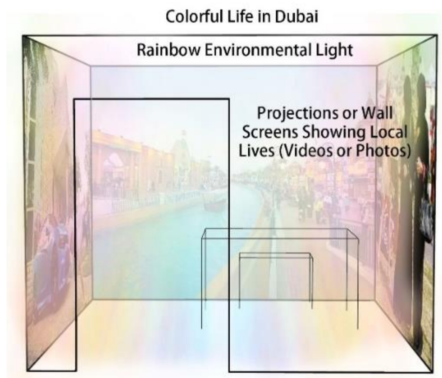
Place-based Cues *to multi-media display*		Using images, videos, audios, and lighting to evoke a remote place that might stimulate creative thinking. The Space Agents might work in concert with this audio-visual output, rendering the whole "portal" to somewhere else.

Table 3. Five human-environment interaction patterns and their corresponding design patterns.

As Alexander et al. reminds us, "no pattern is an isolated entity"—a pattern can only exist "supported by other patterns: the larger patterns in which it is embedded, the patterns of the same size that surround it, and the smaller patterns which are embedded in it" [1]. For the few patterns presented in this paper, each of these patterns can follow another one in time; and at one time, one pattern can be layered upon another one, which collectively constitute larger patterns. In Table 3, for instance, the author sees the design patterns not operating in isolation (e.g. only the Space Agent's impact, as presented in the uppermost row) but combined with the effects found in rows beneath it, so that the space-making robot operates in concert with the lighting effects and audio of the room to offer Place-Based Cues [26].

Admittedly, each of the patterns presented in Table 3 require further investigations to ensure that human users understand the conveyance of the human-like interactions offered by the space-making robot. Such experiments would undoubtedly alter the patterns of Table 3 and may yet generate additional patterns which would, as Alexander et al. offer, represent "more true (sic), more profound patterns" that over time become "a common language, which all of us can share" [1].

VI. FUTURE WORK

The future work involving human participants will

(a) investigate if and how-well distinct patterns generated through the case study communicate (e.g. enthusiasm) to participants as intended, and

(b.) measure the impact of the Space Agents (i.e. robot surfaces) in their physical surroundings on a single human designer undertaking a design task, as comparted to a control in which two human design partners on the same design task.

Increasingly, our physical surroundings are becoming interactive and intelligent by way of embedded system. The authors here, by no means, contend that this pattern-based design framework is the only or best way to design interactive and intelligent artifacts. However, it is difficult to identify embedded artifacts that are without spatial implications, given their numbers, their networking, and their other, expanded behavior. Furthermore, for such artifacts, we tend to expect from them behavior that are natural and familiar to us—that are perceived by us as collaborative. And so, as design researchers strive for more human-human-like interactions between human beings and their cyber-physical surrounding, this framework holds particular promise.

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SUMMARY

In this chapter, the author proposed the "HAI-based design paradigm for space-making robots" inspired by HAI and HRI literature. Then, based on this proposed design paradigm, the author proposed a "pattern-based, design framework for space-making robots" with the related theoretical and analytical foundations discussed. Three of the author's own concepts: "direct mapping," "conveyed mapping," and "space agency," are also defined for the proposed design framework. Finally, a design exemplar of a "design partner" -like space-making robot is presented as the design validation of the proposed design framework.

For the rest of this dissertation, the author first validated the most important assumption of the proposed design paradigm, which is "people will perceive space-making robots as agents." Then the author investigated what are the user-preferred interaction modes when interacting with this human-like space-making robot, and why certain modes are preferred in certain tasks and scenarios.

However, before validating the proposed design paradigm and further investigating user preferences, the author needs to develop space-making robots for the purpose of empirical user studies and experiments. Thus, for CHAPTER II and CHAPTER III, the author presented the design, engineering, and evaluation of two space-making continuum robot surfaces: one for building scale applications (CHAPTER II) and one for interior scale applications (CHAPTER III).

CHAPTER III

DESIGN AND CHARACTERIZATION OF A NOVEL ROBOTIC SURFACE FOR APPLICATION TO COMPRESSED PHYSICAL ENVIRONMENTS

(IEEE ICRA 2019; http://dx.doi.org/10.1109/ICRA.2019.8794043)

ABSTRACT

(Appendix A2: Summative Video)

Developments of robot arms are countless, but there has been little focus on robot surfaces for the reshaping of a habitable space—especially compliant surfaces. In this chapter the author introduces a novel, tendon-driven, robot surface comprised of aggregated, overlapping panels organized in a herringbone pattern. The individual 3D-printed panels and their behavior as an aggregation are inspired by the form and behavior of a pinecone. This chapter presents the concept, design, and realization of this robot, and compares our prototype to simulations of four physical configurations that are formally distinct and suggestive of how the surface might be applied to habitable, physical space in response to human needs and wants. For the four configurations studied, the author found a validating match between prototype and simulations. The paper concludes with a consideration of potential applications for robot surfaces like this one.

I. INTRODUCTION

Robotic surfaces have seen less development and the work has primarily focused on interface devices with variations of continuous [1], discrete [2],[3], and soft [4] surfaces. As the author will address later, there has been little exploration of robot surfaces, especially compliant ones, which morph to define habitable, physical spaces (physical environments) that give shape to the human activities within them.

Research on robotics applied to the built environment has mostly been focused on the fabrication of conventional buildings by industrial robots (e.g. [5], [6]) more than on physical environments with embedded systems—architectural robotics [7]. Nonetheless, the potential opportunity for robot-embedded physical environments is surely to expand, due to a host of trends, including: mass urbanization (a need for more efficient and flexible housing), an expanding elderly population (a need for "enabling" housing and healthcare facilities), skyrocketing real estate speculation (a need for 24-hour, multi-use spaces in high-cost districts), a refugee crisis (warranting deployable healthcare and command infrastructures), autonomous cars (a reimagined car interior for idle occupants), and spacecraft and space habitation (for long-term travel and exploration). Most these cases are detailed in Chapter I with literature backup and graphical illustrations. For these wide-ranging, potential applications, robot surfaces are envisioned forming "many physical spaces" from a single habitable volume—an attribute characterized, in a word, as compressed.

The "compressed" environment is a concept found in A Pattern Language (1977) [8], a book associated with co-author and architect Christopher Alexander which has impacted research on human-robot interaction (e.g. [9]), software engineering (e.g. [10]), and computer games (e.g. [11]) in addition to environmental design. As elaborated in A Pattern Language, a "compressed" environment contains all the functions of a typical building (e.g. a house, a school, a medical clinic) within the confines of a single room. Since the publication of A Pattern Language, the (increasingly) less costly and more capable means of robotics promise to remake the built environment as interactive and intelligent [12]—“robots for living in,” in the words of William Mitchell [13].

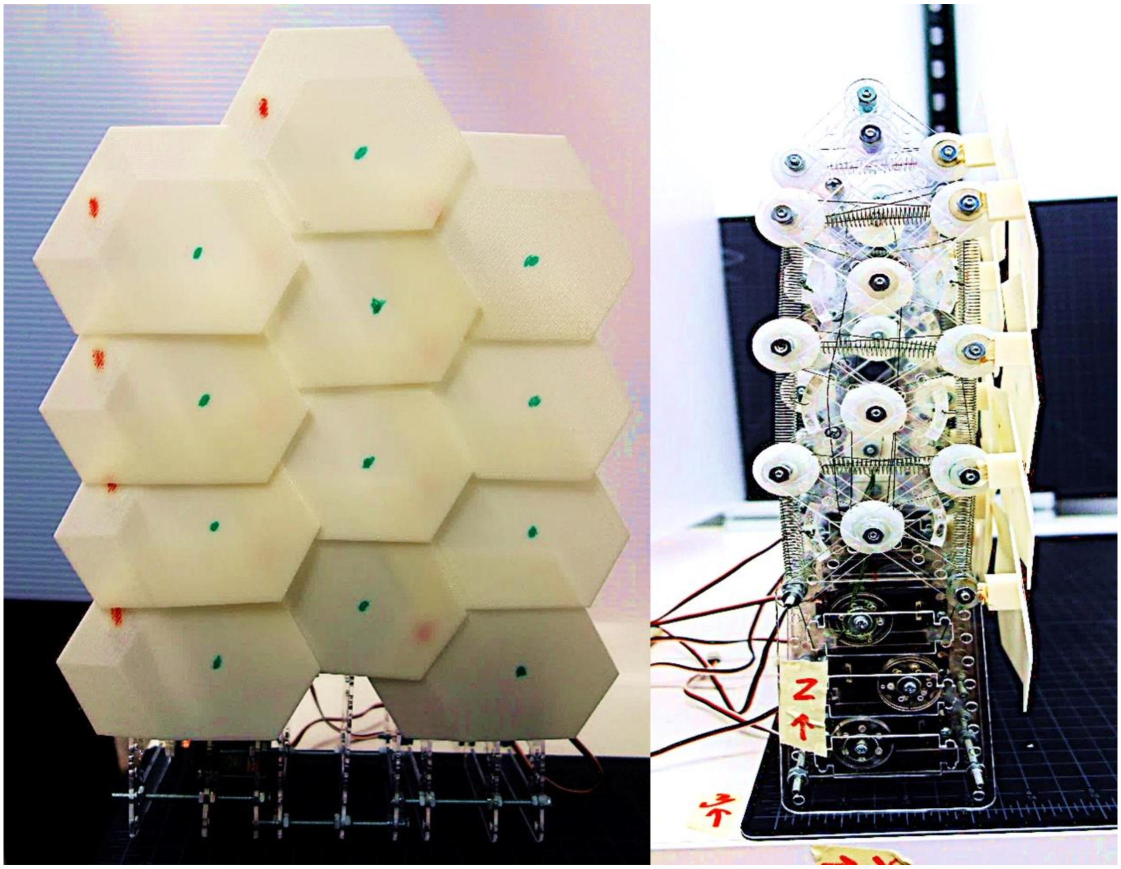

Figure 1. CompResS—a Compressed Robotic Surface (Front & Side).

The author here defines a compressed pattern environment as comprised of malleable, adaptive, physical surfaces dependent on moving physical mass to arrive at shapeshifting, functional states supporting and augmenting human activities. In this paper, the author presents the prototype of such a surface: CompResS—a Compressed Robotic Surface (Fig. 1). As a self-supporting surface, CompResS is a robotic surface capable of morphing in two dimensions, affording the potential of creating habitable spaces that can be—theoretically at least—always different.

II. PREVIOUS RELATED WORK

Before considering the design and characterization of our novel robotic surface, the author has already reviewed multiple space-making robot surface examples in Chapter I, including HypoSurface, MuscleBody, InteractiveWall, and Animated Work Environment (AWE). Please refer to Chapter I for details of these projects.

III. SYSTEM DESCRIPTION AND CHARACTERIZATION

The overall objective for CompResS was to design a reconfigurable, space-making surface applicable to the built environment with sufficient flexibility and control to achieve a multitude of room enclosures supporting wide-ranging human activity, and to meet the expectations of inhabitants. While an origami-inspired folding structure of hinged, rigid links (akin to our AWE [14] or Pop-Up Origami [15]) might achieve something of this objective, a smooth, compliant, continuum-like, robot surface was the preferred approach, given the soft and fluid motion of a continuum surface—qualities better matched to shaping the intimate physical surroundings of human inhabitants than would be a rigid, link - and - panel approach. Additionally, a continuum surface with its theoretically infinite degrees of freedom promises more formal "nimbleness" in creating a greater variety of physical room enclosures compared to an origami-like structure. The research team also has considerable experience in continuum robotics (our overview of this, [16]); nevertheless, the CompResS surface represents an approach not realized prior to this work.

A. Theoretical Approach

In designing CompResS, the author drew inspiration from nature, specifically in systems exhibiting behavior the author sought in a compressed robotic surface. The author considered and experimented with several natural systems – among them, water waves, pineapple skins, and fish scales – to identify a promising model of inspiration. In prior work [17], the author reported on the simulations of three such surfaces, inspired by three distinct natural systems, converging as a research team on one formal approach to the surface's design inspired by the pinecone. The author finally decided to adopt the pinecone approach following the evaluation of the animation studies of the three distinct surfaces (Appendix D1 for More Pinecone Inspired Surface Designs).

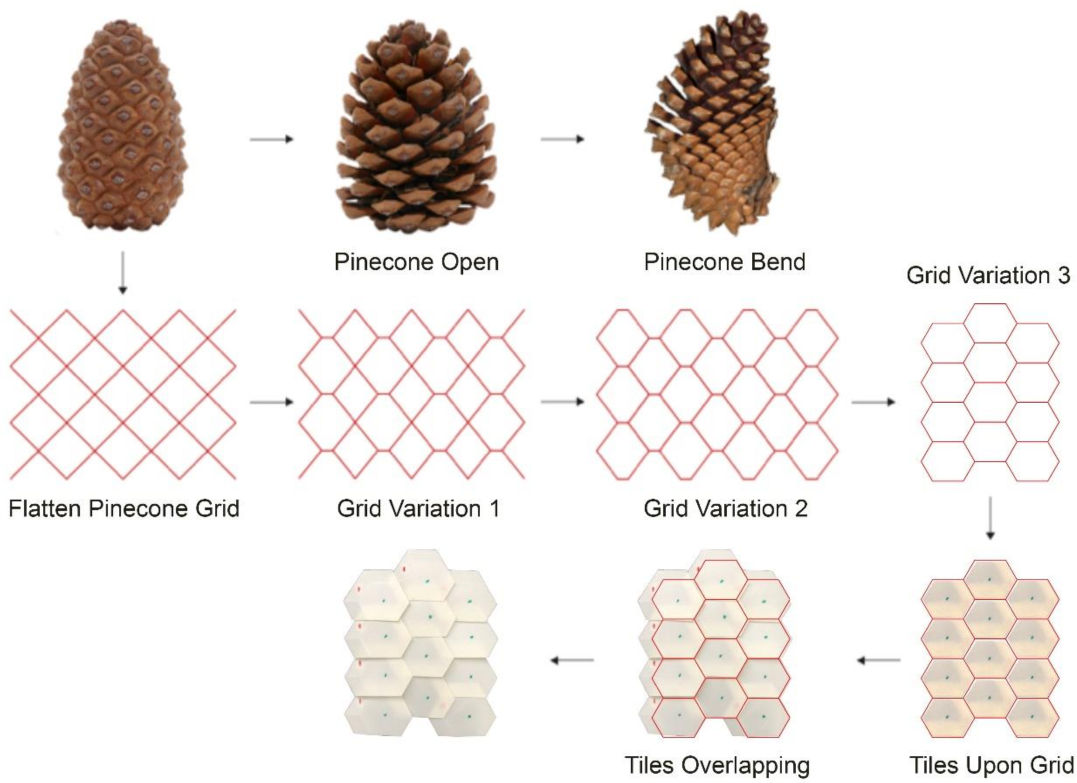

Figure 3. Iterative grid transformation resulting in the patterned scales of our Pinecone-inspired envelope.

The pinecone is a particularly apt inspiration for CompResS, given two attributes: (1) the pinecone aggregation is 3-dimentional and spatial, comprised of similarly shaped and sized units; and (2) the pinecone is not static but instead undergoes cycles of opening, closing and bending during its life span (see Figure 3). As an inspiration drawn from nature, the pinecone lends CompResS the prospect of spatial continuity instead of linear continuity. Here, “spatial continuity” means that, even though each unit (or panel, in our prototype) is moving away from each other during the reconfiguration process (e.g. bending), we still perceive the aggregation as a continuous surface, as the 3-dimentional units are overlapping and slipping past each other.

B. Development of Continuous Grid Variations

With the pinecone as our starting point, we began to analyze the key geometric characteristics of this living thing: the logic of translating a promising biological inspiration into a design model (Figure 3). The formal focus of this design development process was the grid. The grid of the aggregation determined how many types of units will comprise the system, and the relationship across adjacent units. Undoubtedly, different grids generate different units and overall aggregation systems; however, as represented in Figure 3, the different grids shown represent different states of a continuous grid in the process of transforming (reconfiguring). Additionally, these abstracted pinecone grid patterns (Grid Variations 1, 2, & 3) reflect similar spatial principles as in other nature-designed aggregation systems, such as fish scales. To develop the dynamic behavior of CompResS, we identified a singular state of this continuous grid transformation as the grid that generates our design system. As shown in Figure 3, the author used pinecone grid "variation 3" as the starting point for detailed design development of the aggregation of units (i.e. pinecone panels of the compressed robotic surface).

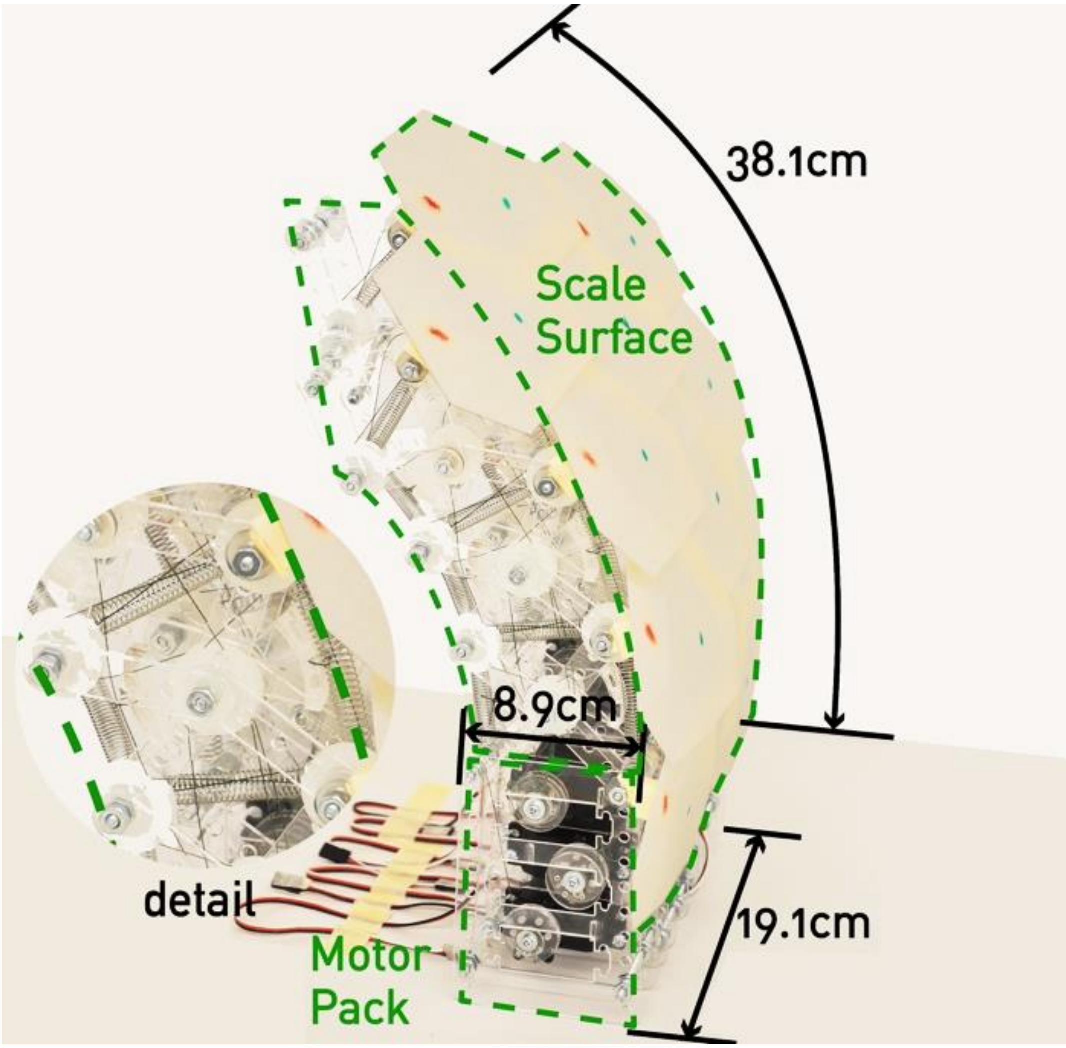

Figure 4. Section views of the built prototype.

Given the identified grid and aggregation units, the author then modeled the units as an aggregated, “curved” surface divided by the grid. Our surface (Figure 1) is designed to form an ample segment of a physical enclosure, with potential for application to the built environment. In the design process, the author then proceeded to populate the units to create a surface as would be found in a natural pinecone. the author then simulated the possible reconfiguration of “Open & Close” and “Bending” found in naturally occurring pinecones. In the simulations, transitions between reconfigurations proved to be very smooth, as previously reported [17]. Our subsequent challenge, reported here, was to design and evaluate a physical prototype capable of achieving physical configurations that were natural but also space-making and, so, capable of shaping human activity.

C. Prototype Design

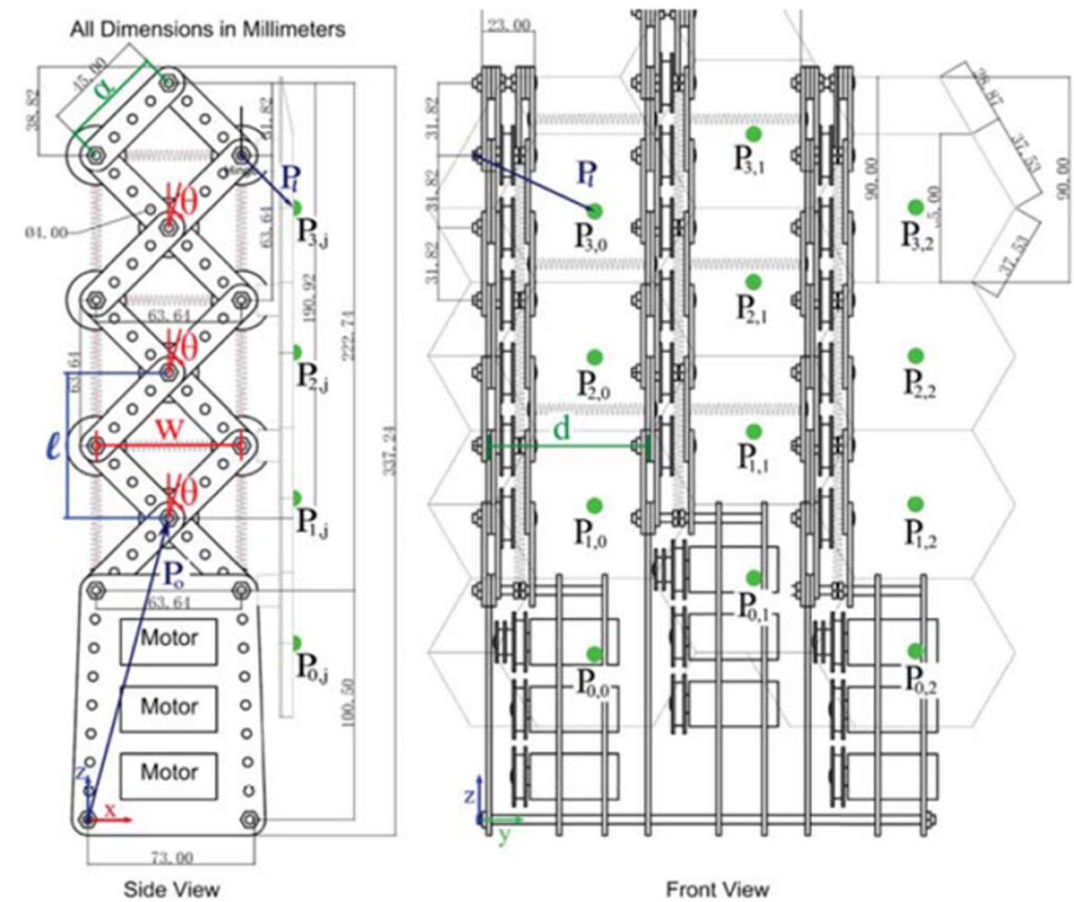

Figure 5. Section drawings of the prototype with all its dimensions and identification of three critical angles and length.

The photograph of the physical prototype (Figure 4) shows the space-forming, pinecone-inspired panels that form the continuous surface, and its skeletal mechanism that actuates this surface. The technical drawing (Figure 5) meanwhile presents the design, in sections, of the “surface-structure” relationship for the built prototype. The overall surface of our built prototype (Figure 4) is 19.1 cm wide by 38.1 cm (when slightly bent), supported by a base 8.9 cm deep. the author scaled this early, physical prototype at 1:10 so that it was adequate in size to characterize and to perform the analysis reported in the next sections, as well as to require no more than low-cost, readily available hardware.

The physical prototype proved sufficient enough in size and number of panels to study the shape-forming behavior of the underlying surface of such an envelope. The structure of the physical prototype consists of three identical, hinged trusses standing upright (Figure 4 and Figure 5), with the center-located truss positioned one-half “pinecone” panel higher from the base than the two outer-located trusses, thereby achieving the space-forming, continuous, herring-bone organization of the surface panels (as presented in Figure 3—the bottom-right diagram).

Each vertical truss (see Figure 5) is composed of nine springs, nine pulleys, and twenty-four rigid truss members of identical dimensions, digitally cut from acrylic (transparent thermoplastic) sheets. The acrylic members are connected by bolts functioning as hinges to create a scissor-like truss. Nine springs are connected to the acrylic truss members where they hinge; these springs are oriented in square formation to create resistance within the truss. At each hinged connection, a 3Dprinted “pinecone” panel is attached by digitally-cut, acrylic components. While these panels are 3D printed in hard plastic, they are nevertheless relatively flexible, given that their thickness is a mere 1mm. This flexibility in the panels allows their edges to slide past one another to form an essentially continuous surface.

D. Electrical Hardware Design

At the rectangular base of the prototype sit six HP-2112 continuous servomotors, two motors per truss (a third motor per truss is seen in Figure 5, but is not used in this work). Each motor is fitted with a pulley to drive a tendon attached to the truss structure. For each truss, one motor controls the continuous bending behavior of the truss in the direction of the surface, while the other motor controls the continuous extension of the truss by decreasing the height of the truss. The design easily bears the weight of the prototype's surface and structure.

For this early prototype, the system is controlled by a circuit of multiple potentiometers. Each potentiometer controls the rotational speed of a motor. There is also a push button connected in-series with a pull-up resistor that determines the rotational direction of the servomotors. The servomotors are connected to the analog pins of an Arduino Uno microcontroller, and the push button is connected to the digital pin. The software functionalities for each component is implemented in Arduino C code and uploaded to the Arduino board. In future work, the author plans to use sensors and machine learning to realize both interactive and intelligent control of the built environment.

E. Structure and Surface Characterization

When the nine springs are added to each truss assembly in this prototype, and when the three trusses are connected themselves by springs, the resulting, composite structure offers a coordinated, flexible armature for the aggregated pinecone surface panels.

Each robotic truss is designed to have two basic motions: extending (Figure 6.B and C) and bending (Figure 6.B), either of which can occur separately or simultaneously (as in Fig. 6.B). Consequently, each robotic truss can assume four different physical states: (1) static, (2) bending, (3) extending, and (4) bending and extending. Given the three trusses that make this prototype, this prototype can assume a total of sixty-four different physical states irrespective of motor function (e.g. speed and rotational angle). Although each robotic truss moves within its own sectional plane, the composite system of three trusses gives this robotic surface the freedom of bending perpendicular to the sectional plane because of the spring connections between the three trusses. This affords the very organic behavior of the continuous robotic system in the process of reconfiguring (as presented in our supporting video).

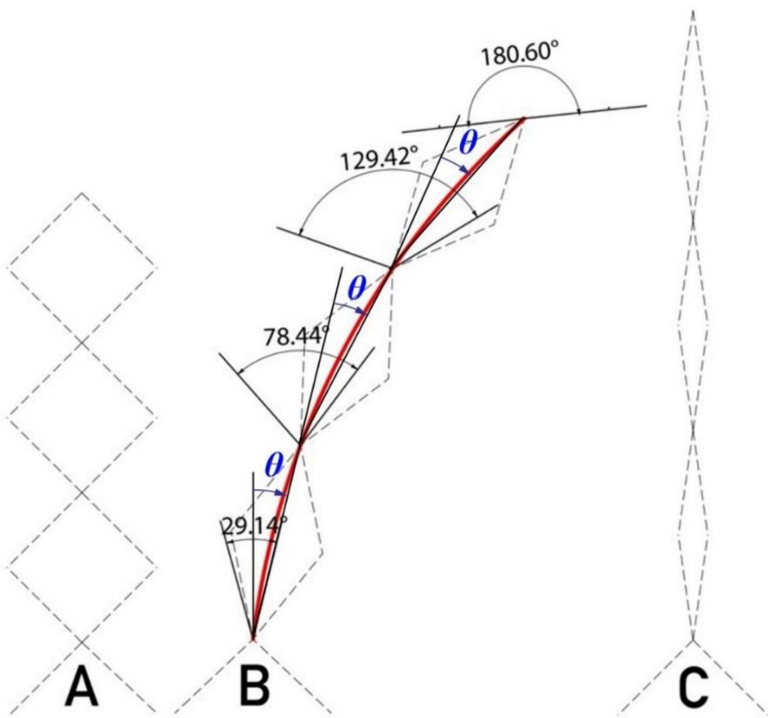

Figure 6. Range of motion, in section (A) fully-contracted and vertical; (B) bent and extended; (C) fully-extended and vertical.

IV. KINEMATIC MODEL

As mentioned in the previous Section, the variables to manipulate the shape of a single truss within ComPresS are **w**, the width of the scissor directly manipulated by tendons, and θ, the bending angle of each mechanism. A kinematic model was developed to relate the variable parameters of each truss (i.e. **w**, **θ**) to world coordinates for a series of discrete points along the surface of ComPresS. The model assumes that the value of **w** and **θ** are constant along the length of each truss. The first step in describing the model was to convert the width of the truss to the extension along the center. The local extension is given as

l=$\sqrt{4\alpha^2 - L^2}$,

where **l** is the local extension, the value α is the constant length of one side of the scissor (4.5cm for CompResS), and **w** is the width of the truss, as stated previously.

Given the length and rotation for each truss, we can treat the motion as a planar robot with alternating revolute and prismatic joints. A transformation matrix could be derived to describe this motion; but for simplicity. we can describe the location of a desired point along the surface using the following equation:

$$P_{i,j} = \begin{bmatrix} x_{i,j} \\ y_{i,j} \\ z_{i,j} \end{bmatrix} = \sum_{n=0}^{i} \left(\left[R_{y,\theta_j}\right]^n * \begin{bmatrix} 0 \\ j * d \\ l * n \end{bmatrix} \right) + [R_{y,\theta_j}]^i * P_l + P_o$$

The point $P_{i,j}$ is the *i*th discrete point along the *j*th truss on the surface. The matrix R_{y,θ_j} is the standard rotation matrix around the y-axis by θ_j [14], measured with respect to the base frame. The values d and P_i represent the constant distance between two adjacent truss mechanisms along the y-axis and the local offset of the measured points from the center-line of the truss, respectively. The constant P_o is the offset relating the world coordinate system to the local coordinates of the surface. The orientation of each discrete point, and the plate corresponding to that point, can be described simply as $\theta_{i,j} = i * \theta_j$.

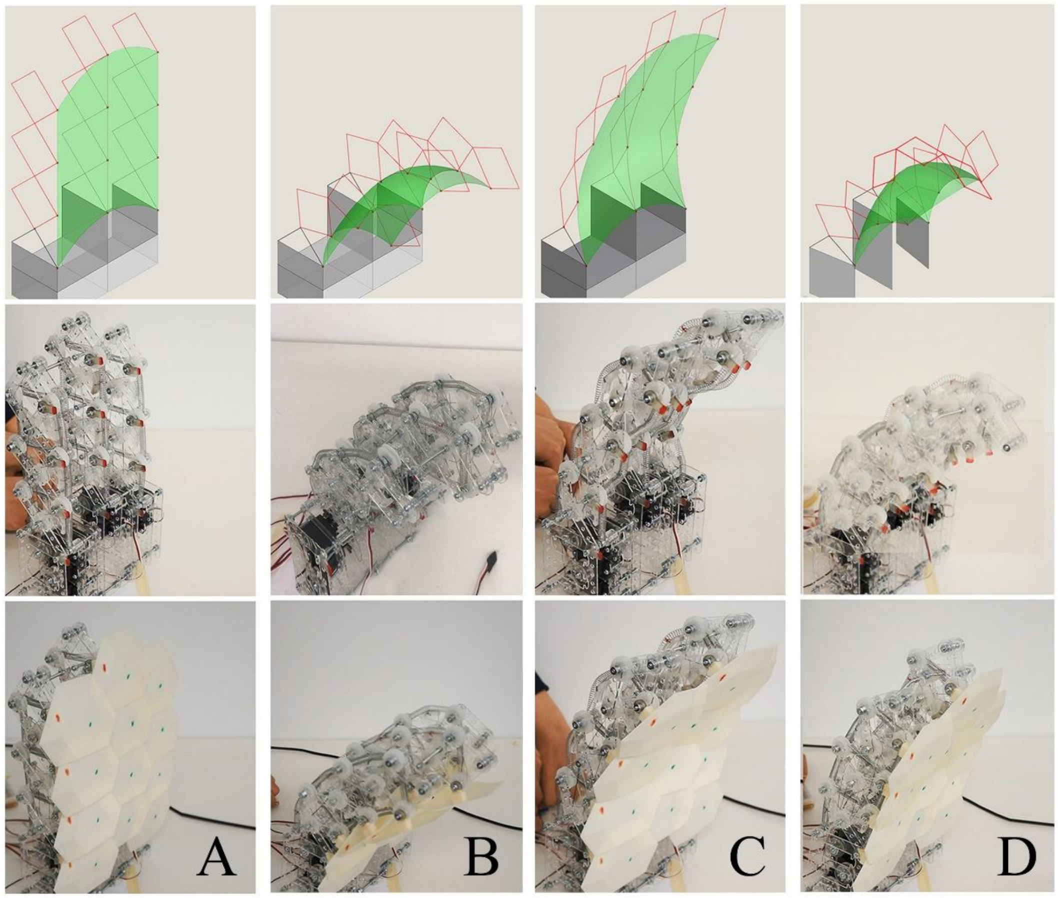

Figure 7. Experiments with shape-forming: 5 essential configurations (A) upright; (B) forward-bend; (C) forward-extend; (D) angled

V. EXPERIMENTS, IN SIMULATION, IN SHAPE MAKING

the author conducted an analysis of the shape-making capabilities of the surface prototype. For this, the research team identified four physical configurations that represent both a shape and a user-centered lexicon of distinct, space-forming shapes. Further, these four configurations well-characterize the physical capabilities of the design. As shown in Fig. 7, these four physical configurations are: (A) upright, (B) forward-bend, (C) forward-extend, and (D) angled. While the four configurations are formally distinct, suggesting the wide-ranging configurations the surface can assume, the four configurations are also suggestive of how the surface might support human need and wants. For two instances of the latter, we can image how (A) upright serves as a projection surface (or wall) for viewing larger images, viewed by a larger group, whereas (B) forward-bend forms an intimate space wrapping a single person or pair of people focused on reading, relaxation, or meditation. The four configurations were initially simulated as fixed (i.e. static) graphic images using parametric software (see Figure 7—top row).

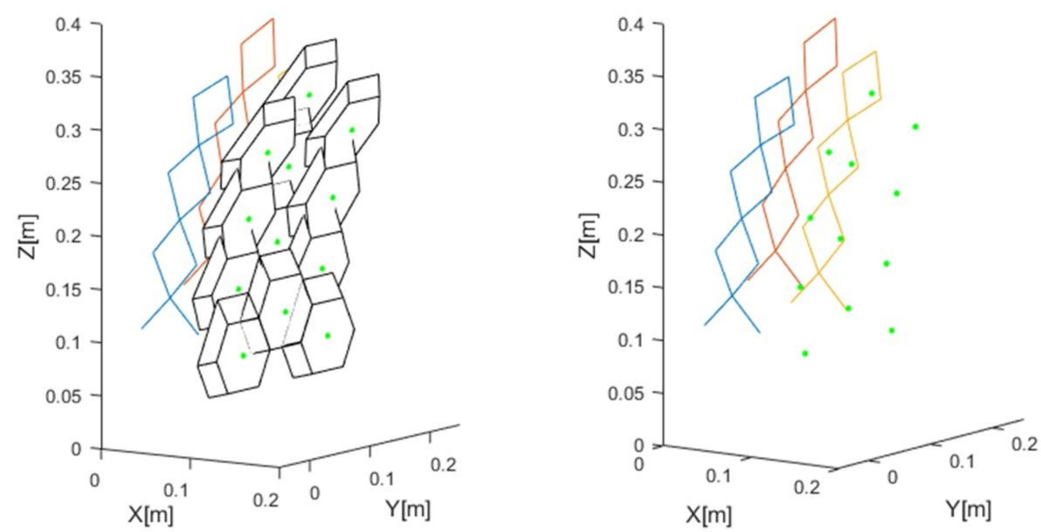

Figure 8. Simulation model of CompResS.

A. Simulation Model

Using the kinematic equations and the measurable constants of the physical system, a simulation model of CompResS was developed using MATLAB. As with the physical device shown in earlier Figures, the simulation shows the shape of each truss and the position and orientation of the interlocking plates of the robotic surface. An example of the model can be seen in Figure 8, where the left image shows the shape of

CompResS and a series of discrete points in green, and the right image simulates the orientation and placement of the plates with the same series of discrete points. The simulation does not capture the physical interaction of the plates on the surface, so the simulated plates are not restrained from intersecting or overlapping. This simulation model was used to predict the location and shape of the CompResS surface for each of the proposed configurations.

B. Experimental Design

With the physical prototype, the author then studied whether its trusses (without the attached surface panels) could assume the four truss configurations offered in the simulations. Similarly, with the physical prototype now fitted with the surface panels, we examined whether the surface could assume the four surface configurations offered in the simulations (Figure 7— bottom row). the author then tested each configuration and its smoothness of movement from a "position of rest" ("A") to the prescribed configuration ("B," "C," "D") by observing the motion. In addition to observing motion, we took measurements of the length between each truss, the angle of truss formation, and the three-dimensional location of each of the twelve panels (see these identified in Figure 5) for each of the four configurations. the author accomplished this by measuring the position of each green dot (see, e.g., Figure 1) in the x, y, and z direction in reference to the prescribed origin in the bottom, back corner of the CompResS (Figure 5). There was some error due to the measurements being taken by hand. However, by using precise measurement tools and taking multiple measurements, this data proves to be an accurate description of the various configurations.

C. Results

When observing the transition of CompResS between each configuration, the author found that the design, quite successfully, allowed for smooth transitions regardless of the start and end configuration. The author also noted from the observations that the physical prototype convincingly assumes the design states of the simulation for all four configurations.

In order to compare the physical experiments to the simulation, the research team calculated the error between the physically measured locations of the twelve points and the corresponding points in the simulation. Table 1 summarizes the results of the experiments versus the simulations for the 4 configurations.

Cfg.	Kinematic Value (L_{avg} [cm], θ_{avg} [°])						Avg. Euclidean Error [cm]
	Truss 1		Truss 2		Truss 3		
A	7.0	0	7.0	0	7.0	0	1.2
B	6.9	26	6.5	25	6.5	26	3.2
C	5.6	11	5.8	16	5.8	11	2.4
D	4.9	8.3	4.1	8.3	4.8	8.3	2.8

Table 1. Summary of Results

VI. DISCUSSION AND FUTURE WORK

A. Discussion

It was clear from observations during the testing of each configuration and from deviations between the measured configurations and simulated configurations, that the surface panels, in their current design, physically hinder one another and, thus, the trusses, so that the resulting surface geometry is distorted. Although the author realized the scales will hinder each other in the current design, the author did not change the design before building the final physical prototype because the 1 mm thick plastic scales seemed to be too soft to obstruct the movement of the continuum structure. However, the author underestimated the rigidity of the plastic scales and overestimated the power of the motors. In particular, (B) is not as precise as anticipated from the configurations assumed by the physical prototype without the surface panels mounted. This physical hindrance between the plates led to non-constant bending in each truss which caused increasing error along the length of each truss.

In reporting the Euclidean error, it is notable that the average error is greatly influenced by small errors in angle measurement and non-constant bending. In configuration B, which had each truss bending as far as possible and the largest resulting error, the restriction of the surface plates caused the first bending point to bend more than the other two points on the truss. This allows CompResS to assume the general desired shape but causes larger errors near the top of the surface.

Many of these configurations were tested at the maximum range of motion for the system, either along the length or maximum bending. With the edition of the restrictive surface, there is expected to be error between the ideal simulation and the physical device.

B. Future Work

The hindrance caused by the mounted surface panels suggests the need for future work geared towards the redesign of the surface panels in order to allow for smoother overlap and movement in all the desired configurations. A possible approach to the redesign of the panels would be reproducing the current panels with soft materials such as silicon or rubber to avoid the interference caused by the rigidity of the current material.

Refinement of the tendon-driven, servo-motor structure could allow for more smooth and efficient movement. Further, the programming of CompResS could help alleviate some of the panel hindrance while increasing efficiency in transitions between configurations.

Along with addressing the physical restriction of the panels, it is desirable to enhance the actuation system with a series of brakes to hold a desired configuration. This addition will remove the need to constantly power actuators in order to fight the spring force inherent in the device.

Another future task is to find a more accurate means of measuring the angles of the trusses and locations of the panels in each configuration. One option is to use motion tracking technology such as the Microsoft Xbox Kinect. Potentiometers or encoders could also be placed along the truss joints to accurately measure the degree of bend and change in length.

It will be desirable in the future to expand the kinematic model to describe the surface of the robot, such as concavity or gradient, instead of describing discrete points. This, combined with an inverse kinematic model, could allow a user to describe a shape or desired plane for the robot surface to create.

VII. POTENTIAL APPLICATION

A potential application of the CompResS is in public spaces such as illustrated in Figure 9, to create a playful and interactive shopping experiences. This is one of many applications for robot surfaces—a list of which was mentioned at the start of this paper, and more details can be found in Chapter I. The author welcome the challenge of developing a robotic surface at room-scale that is more capable of forming an enclosure that envelopes its inhabitants. CompResS is our initial step in achieving this objective.

Figure 9. ComPresS creating interactive shopping experiences.

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CHAPTER IV

DESIGN AND CHARACTERIZATION OF A NOVEL, CONTINUUM-ROBOT SURFACE FOR THE HUMAN ENVIRONMENT

(IEEE CASE 2019; http://dx.doi.org/10.1109/COASE.2019.8842988)

ABSTRACT

(Appendix A3: Summative Video)

The author presents a novel, space-making robot aimed at adaptively automating the shape and functionality of the human environment. While robots tend to be rigid-link, stiff objects when set within human environments, serving specific human objectives, they can also be compliant and give form to the physical environment and widen human activities within it, which is the concept of space-making robot. This chapter presents the design and realization of an interior scale space-making robot, which is a continuum robot surface mechanism. Experiments with this robot surface compare our prototype to our simulations of five spatial configurations that are formally distinct and suggestive of how the surface might be applied to habitable, physical space in response to human needs and wants. The author found a validating match between prototype and simulations for the five configurations investigated. This chapter concludes with a consideration of potential applications for robot surfaces like this one.

I. INTRODUCTION

Robots have tended to be highly functional objects set within a physical space to serve limited and specific human objectives. Such robots are, for the most part, characterized by rigid-link mechanisms, many times manifested as robot arms. There has been little exploration of robot surfaces capable of shaping a physical environment to enable human activities within them, and few such robot surfaces are compliant (i.e. “continuum” robots [1]).

As the author mentioned in Chapter I, space-making robots can be malleable, adaptive, physical surfaces that are dependent on some form of actuation and automation to arrive at a variety of shapeshifting, functional configurations that support and augment human activity in ways perceived as familiar. More practically, a space-making robot herein is a compliant 2D (“continuum”) robot surface that can be controlled to (a) change the shape of space, and (b) interact innovatively with people using it to assist in their environments. Space-making robot surfaces actively expand the affordances of conventional rooms and transform the most confined spaces into, effectively, “many rooms,” and are moreover capable of some manipulation tasks. Applications of space-making robots are described in Chapter I.

Space-making robots will not simply serve humans; they will moreover augment the physical environment to extend the human habitant’s capabilities and potentially add to the productive and creative quality of their work. We have identified five distinct “capacities” of a space-making robot surface: (1) facilitation, (2) simulation, (3) spatial organization, (4) presentation, and (5) stanchiation (see Table 1). In order to exhibit these five capacities, users will need to interact with the robot, and its surface will need to respond by adapting its shape. This paper reports on the investigation of five typological configurations of a robot surface that enable these five capacities via human-robot interaction for, especially, the workplace environment (e.g. the office interior, the autonomous vehicle interior, the spacecraft interior).

Capacity	Task Examples
Facilitation	Precisely position a tablet for notetaking.
Simulation	Evoke human emotions or places of interest.
Spatial Organization	Divide or shape the space to support human activity.
Presentation	Position (bendable) computer displays.
Stanchiation	Provide surfaces for physical support.

Table 1. Five "capacities' of the robot surface

II. SCENARIO

Alane, an industrial designer, is designing a table lamp from within her tiny Hong Kong office (which, in the future, could sometimes be an autonomous vehicle). When Alane's clients arrive for a meeting, they are not surprised that her office is so small; they do notice that the office is outfitted with a new technology called Space Agents. Seated at the worktable, Alane and her clients begin reviewing requirements for the lamp design. The Space Agent – a bending panel several-feet long and less than two-feet wide – gently positions a computer tablet for Alane to comfortably note-take without disrupting eye contact or conversation with her clients ("Facilitation"; e.g., see, towards the close of the paper, Fig. 8—left). When Alane's clients offer that the lamp should be inspired by "billowy clouds in the sky," two continuum robot surfaces on the ceiling start gently swaying ("Simulation"; Fig. 8—left) and glow a light-blue. Alane and her clients comment on the simulated "clouds in the sky" environment, noting that "the LEDs are too blue" and that "the surfaces are swaying too fast." The robotic surfaces adjust until the client is satisfied: "Right! This is the feeling!" The parameters of the simulation are automatically saved for later recall. Inspired, Alane starts sketching as her clients follow and respond. Unexpectedly, Alane receives an incoming voice mail message that requires immediate attention. She politely excuses herself and rotates on her swivel chair to respond. The system recognizes these gestures and three robot surfaces gently bend down to divide the small office space into two parts ("Spatial Organization"): one for Alane's private activity and one for clients' discussion (see Figure 3—right). After Alane has completed her response, the workspace's configuration returns to normal. Alane presents her clients another sketch of a possible lamp design. When she points to the wall behind her, a soft robotic surface with a bendable screen displays a presentation ("Presentation"). The meeting goes well, the clients depart, encouraged; but Alane feels tired, and shifts her weight gently against a Space Agent, which conforms to her as she continues to sketch ("Stanchiation"). To capture the mood of the meeting as inspiration, she issues a voice command, and the robot surfaces begin swaying gently and glowing at the rate and in the color saved for recall.

III. PREVIOUS RELATED WORK

Before considering the design and characterization of this novel robotic surface, the author has already reviewed multiple space-making robot surface examples in Chapter I and Chapter III, including HypoSurface, MuscleBody, InteractiveWall, Animated Work Environment (AWE), and ComPresS which is developed by the author. Please refer to Chapter I and Chapter III for details of these projects.

IV. SYSTEM DESCRIPTION AND CHARACTERIZATION

The overall objective for Space Agent was to design a reconfigurable surface applicable to the built environment with sufficient flexibility and control to achieve a multitude of configurations in order to both engage in space-making and human-assistive activities, and to meet the associated expectations of inhabitants. As compared to a rigid-link robot arm, the continuum robot surface is compliant and fluid in motion—qualities better matched to shaping the intimate physical surroundings of human inhabitants and safeguarding them from harm's way [2]. Additionally, as compared to rigid-link actuation, a continuum surface, with its (theoretically) infinite degrees of freedom, promises more formal "nimbleness" in creating a greater variety of physical room enclosures while also performing some manipulation tasks that, taken together, promise greater work satisfaction and work performance. While the research team has considerable experience in continuum robotics [1],[2],[3], the space-making robot surface represents a novel contribution to robotics not realized previously.

A. Theoretical Approach

To inform the development of the space-making robot surface, the author studied the design and behavior of social robots in various environments, such as robots in homes [4] and healthcare [5] with special emphasis on how human may be assisted by robots in activities of daily living [6] as well as tasks in work environments [7].

We envision space-making robot surfaces embedded within the surfaces of a room's ceilings and walls, and offering three specific behavior: space-making, manipulation, and gesture-making. Our prototype (Figure 1) is a tendon-based robot surface featuring remote actuation of tendons running along the surface structure. Such a tendon-driven continuum robot features a smooth, compliant, and continuously bending body inherently suited to operate in close proximity (including interactive and intimate contact) with humans [8]. In addition to being well-suited to humans, tendon-driven designs have the advantage of providing the strength to move surfaces that are large and compliant.

Figure 1. Space-making robot surface—a continuum robot surface.

B. Development of Space-Making Robot Surface Variations

In developing this tendon-driven surface, the research team analyzed the key geometric characteristics needed for the robot to accomplish its primary tasks. The formal areas of focus for this design development process were the malleable surface material and mechanism for motor-tendon actuation. Using a facile, rapid-prototyping method to analyze and compare designs, the author considered a wide variety of tendon numbers, arrangements, and termination points. The author also considered surfaces of different materials of singular and composite construction with different physical properties (e.g. stiffness, density, etc.). Further, motor-tendon combinations had to be sized to ensure that the (inherently compliant) continuum surface selected for the full prototype: (1) could achieve a range of “striated and smooth” configurations; and (2) could be provably safe and viable to all users.

C. Prototype Design

Figure 2 shows the reconfigurable, tendon-driven robot surface prototype. Initially, a 72”x24”x2” foam was utilized for the prototype; however, upon determining that a high-level of malleability, and the generous width of 24” would result in a lack of dexterity, 72”x14.5”x2” was chosen as the dimensions for the prototype. Before arriving at this final prototype, the author together with the research group iterated the material of the continuum robot surface several times. Figure 3 shows a foam material that is too soft to be for controllable shapes during previous iterations. In the end, the foam used for the final prototype is a white polyethylene foam supplied by New England Foam (USA). For a tendon-driven design to work, the tendon needed to be affixed to the surface at various lengths along the surface. As was analyzed in the development of the robot surface design, the number of tendons and arrangement, as well as where the tendons were attached would greatly affect the configurations the robot surface could achieve. Future iterations of the prototype may include varying materials across the surface which would affect its dexterity and potential configurations. However, the design reported herein worked well for the purposes as it could be accurately modeled kinematically (section IV) and reconfigured to adequately achieve the desired configurations.

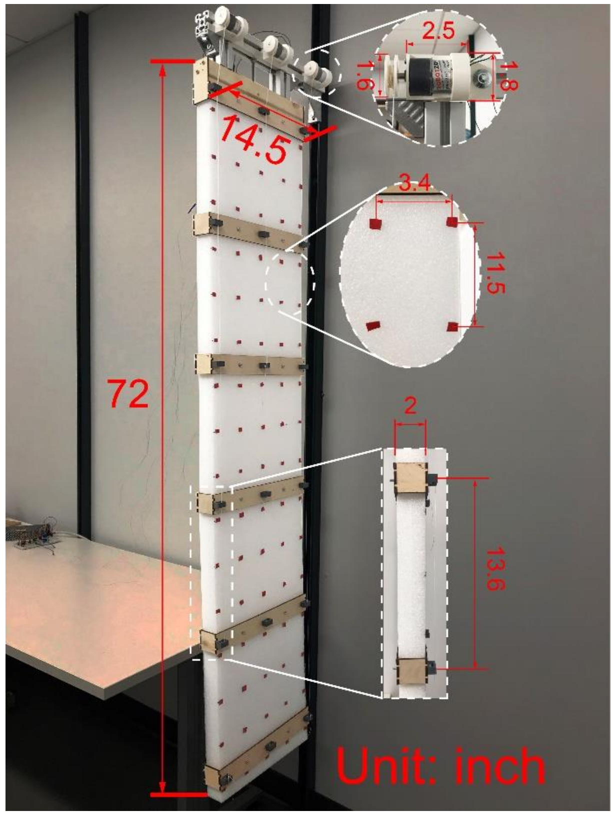

Figure 2. Dimensions of the built prototype.

For initial testing purposes of the robot, three nylon, non-stretching tendons were chosen to run straight along one side of the surface, from the top of the robot surface prototype (where the three tendons are attached to three geared motors) to varying points along the robot surface. The outer two tendons run the full 72" length, while the middle tendon is attached to the surface at about 30" from the top in order to enable a greater variety of possible configurations.

The prototype features six "collars," evenly spaced along the length of the foam surface, which are constructed from laser-cut wood and 3D-printed, plastic "tendon guides." Each collar was made of four interconnecting wood pieces, and each 3D-printed piece featured a hole through which the tendon was threaded and attached. The tendon guides "guide" the force exerted by the motor on the tendon along the length of the surface. The top collar features a physical extension to a mount accommodating the actual motors. High-torque motors were chosen to easily actuate the robot into the five configurations. A video supporting this paper features the prototype, in real-time, forming the five physical configurations (see https://vimeo.com/320610494).

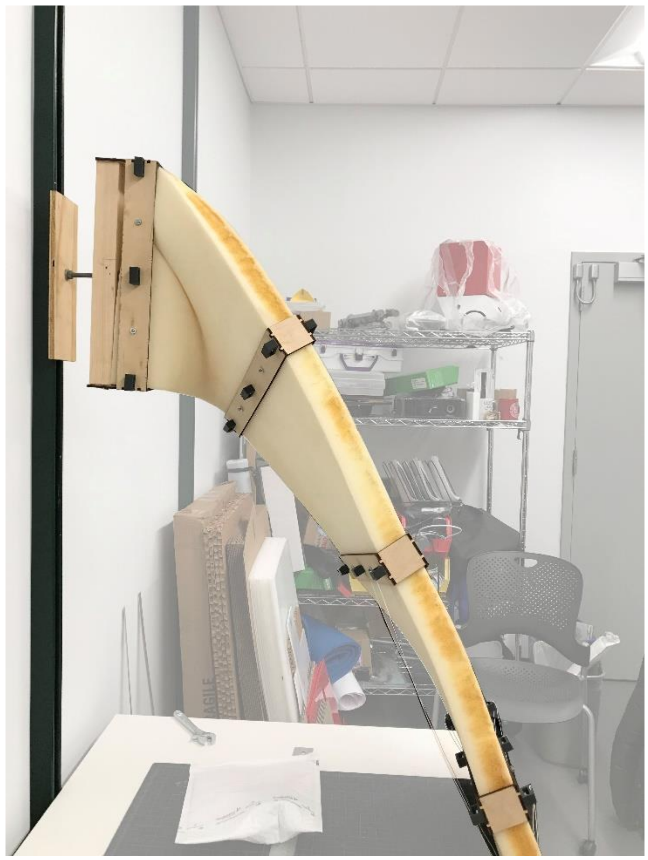

Figure 3. Design iteration process: a foam material too soft to be controlled by tendons.

D. Electrical Hardware Design

Above the mount of the robot surface prototype, there are three 12V, high-torque motors capable of generating enough force to reconfigure the surface robot. Each motor was fitted with a pulley to drive a tendon attached to the surface. For each tendon, the motor either winds (or unwinds) to generate a configuration (or release it).

One advantage to this electrical set-up is that, in a real physical space, the electric motors, mounted above the ceiling and behind fixed walls, will actuate the tendons. Thus, the tendons can be routed through the interior of the flexible surfaces and arranged to terminate at various points in the surface, allowing for an infinite number of shapes. This design also enables future iterations of the prototype to include a variety of other interactive control systems to further facilitate human-robot-interaction.

E. Structure and Surface Characterization

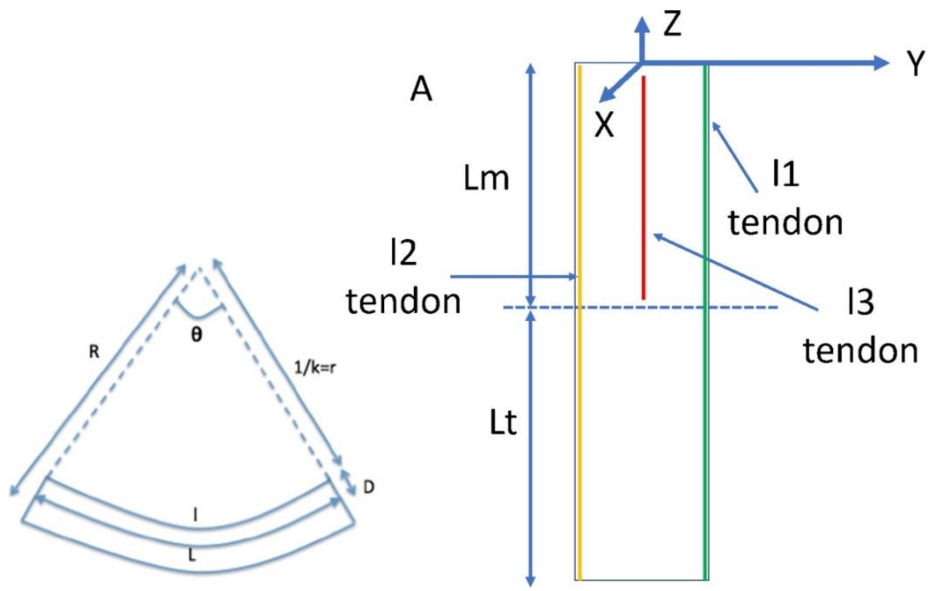

Figure 4. Labeled variables (A) Curvature, (B) Dimensions

The resulting composite structure of the prototype (Figure 4) offers a coordinated, flexible surface capable of achieving a variety of configurations. Winding and unwinding of the three tendons by the three motors to varying degrees results in five fundamentally different physical states: (A) rest (flat and rigid), (B) strong bend, (C) soft bend, (D) twist and (E) angled. While these five configurations have been identified for the purpose of our research, the basic surface design could potentially achieve an infinite number of configurations with a variety of alternate tendon arrangements, motors, and material density.

Although each tendon pulls the surface in a single dimension, the composite system of three tendons gives this robotic surface the freedom to bend in organic, continuous motions in the process of reconfiguring in 2D, as presented in Appendix A 3 Video: Design and Characterization of a Novel Continuum Robotic Surface.

V. KINEMATIC MODEL

In order to model the configurations of the space-making robot surface, a kinematic model was developed as a validation tool for the surface's movements. The first step in determining a kinematic model for the surface was to relate a curvature value to the location of the tendons [9]. This was done using the relations between angle, arc length, and radius with the variables shown in Fig.4(A) which depicts a schematic side view of the surface, the bend angle, and curvature. Fig.4(B) depicts the labeled dimensions from a front view.

Tendons $l_1 \in \mathbb{R}^{+}_{0}$ and $l_2 \in \mathbb{R}^{+}_{0}$ control the deformation of the entire surface whereas tendon $l_3 \in \mathbb{R}^{+}_{0}$ control the bending up to the midpoint of the surface. Due to the way tendons routed, we can identify two bending sections of the surface, denoted by the surface lengths $L_m \in \mathbb{R}^{+}$ and $L_t \in \mathbb{R}^{+}$. The surface has a w width with $L_m + L_t$ length. In addition, the intermediate points of the surface between the tendons l_1 and l_2 undergoes a linear combination of the length change given by $l \in \mathbb{R}^{+}_{0}$ as

$$l = \frac{(l_1 + l_2)w + 2y(l_1 - l_2)}{2w} \qquad (1)$$

Where $y \in [-w/2, w/2]$ is the distance along the y axis to point length is measured.

Due to the coupling of sections, tendon length changes are distributed to sections, denoted by l_m and l_t corresponding to m and t sections as follows

$$l_m = \frac{L_m l}{L_m + L_t}, \quad l_t = \frac{L_t l}{L_m + L_t} \qquad (2)$$

Associated with these length changes, the sections of the surface bend in a circular arc shape. Considering the original length and tendon lengths, without losing generality, we can write a relationship between the length changes given by (2) and arc parameters (Fig. 5).

$$L_k = (\lambda_k + d)\theta_k \qquad (3a)$$

$$l_k = \lambda_k \theta_k \qquad (3b)$$

Where $\lambda_k \in \mathbb{R}^+$ is the radius of the arc, $\theta_k \in \mathbb{R}$ is the angle subtended by the arc, d is the surface thickness, and $k \in \{m,t\}$ denotes the section being considered. Note that, if $k = m$, l_3 length change can be substituted to l_k in (3b).

Solving (3) gives us the curve parameters

$$\lambda_k = \frac{d l_k}{(L_k - l_k)}, \quad \theta_k = \frac{(L_k - l_k)}{d} \qquad (4)$$

Now, utilizing the curve parameters, we can derive the transformation matrix, $\mathbf{T}_k$, associated with any k^{th} section as where $\mathbf{P}_s \in SE(3)$ and $\mathbf{R}_s \in SE(3)$ are homogeneous translation and rotation matrices along and about the axis s.

Utilizing (5) and standard coordinate transformations, now we can derive the homogenous transformation matrices for sections m and t as $\mathbf{T}_m$ and $\mathbf{T}_m\mathbf{T}_t$.

VI. SIMULATIONS AND EXPERIMENTS

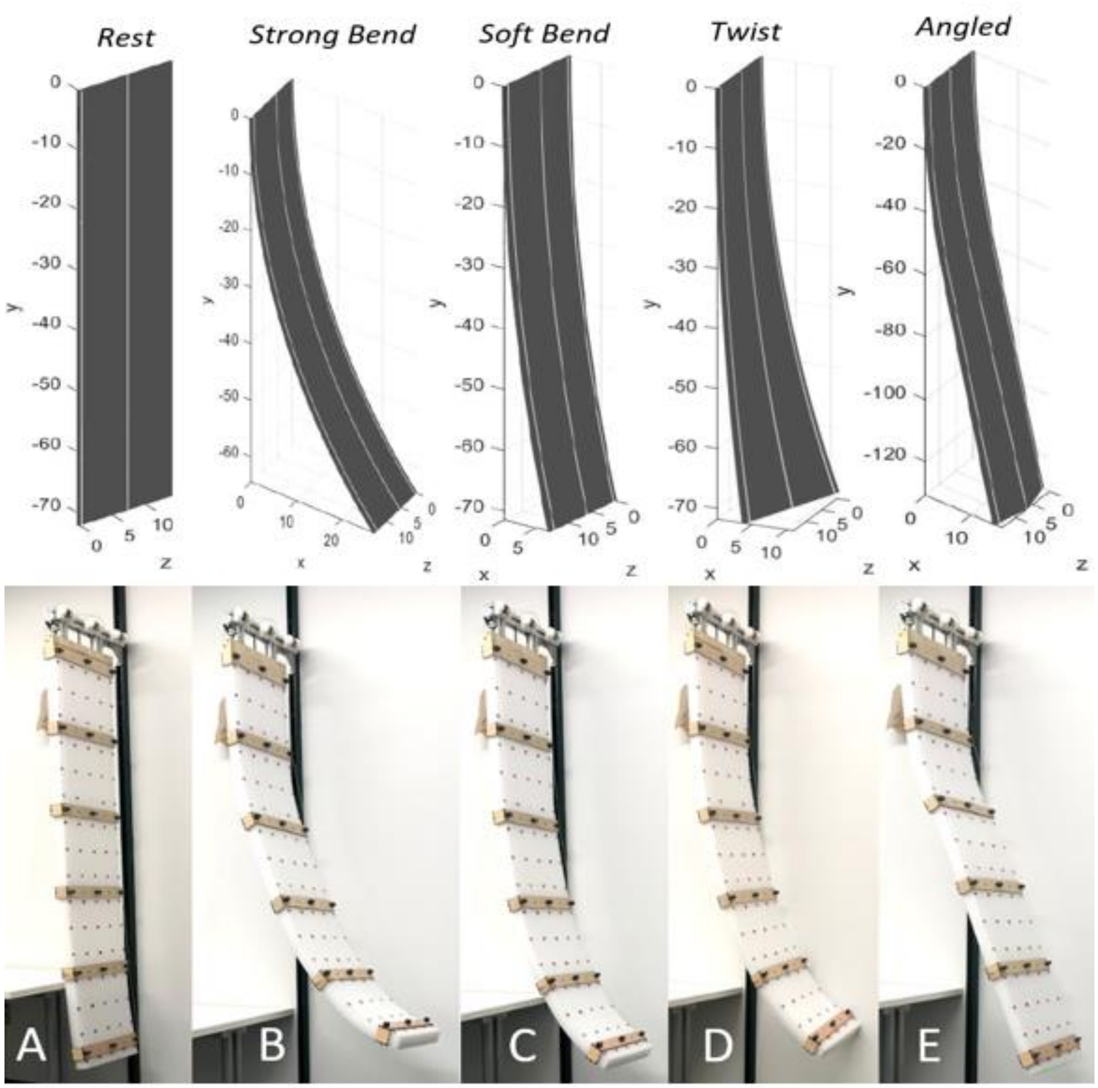

Figure 5. Top Row: Simulation of 5 Configurations, Bottom Row: Prototype Images of Configurations.

The author conducted an analysis of the shape-making capabilities of our surface prototype. For this, the research team identified five physical configurations that represent both a shape and a user-centered lexicon of distinct, space-forming shapes that afford the five capacities of the robot in supporting human activity (see Table 1). Moreover, these five distinct configurations well-characterize the physical capabilities of the prototype. While these five configurations are formally distinct, suggesting the wide-ranging configurations the surface can assume, the five configurations are also suggestive of how the surface might support human need and wants. For instance, the author might image how: configuration (A) rest serves as a projection surface (or wall) for viewing larger images, viewed by a larger group; (B) strong bend assists in providing a human with a tool; (C) soft bend might shape an environment; (D) twist serves as a barrier, dividing a workspace between people; and (E) angled can stanchiate (physically support) the tired arm of an overworked person.

A. Simulation Model

Using the kinematic equations in section IV and the measurable parameters of the physical system, a simulation model of the robot surface was developed using MATLAB. In Figure 5, top row, the simulation shows various, configured shapes of the robot surface. This simulation model was used to predict the location and shape of the continuum surface for each of the proposed configurations. Based on the configuration the model needed to depict, the corresponding tendon lengths were generated to render the expected output. This simulation provided the x, y, and z coordinates of points across the modeled surface.

B. Kinect RGB-Depth Mapping (Appendix C for MATLAB Codes)

The research team utilized a Microsoft Kinect camera [10],[11] to compare the depth data at various points on the surface from the kinematic model, to the depth at those points in the prototyped surface at each physical configuration. The camera is a color and infra-red depth (RGBD) sensor which enables the Kinect to capture depth and color images simultaneously at a frame rate of up to 30 fps [10]. The research team developed a MATLAB program that would capture the depth and color data and generate a point cloud with about 300,000 points of data in a single frame.

The Kinect offers numerous benefits, including requiring minimal hardware for depth and color capture. Further, the Kinect is compatible with MATLAB and renders real-time images and data within an enclosed, indoor environment. The sources of error are also minimal and arise, primarily, from the sensor itself, measurement setup, and properties of the surface [10]. Further, the area of interest can be constrained to a physical area, pixel sensitivity, and a particular color (based on RGB values) to delineate specific data points.

Thus, to triangulate the points on the surface from which the research team wanted to capture data, the author marked the surface of the foam panel with distinct, contrasting red-tape markers as seen in Figure 1 and Figure 2. These markers were evenly spaced. The MATLAB code was calibrated to seek only the RGB values matching the red markers. In order to increase accuracy of the color calibration and only collect data from the red-marker points, high-intensity LED spotlights were used to illuminate the surface against a dark background. This experimental setup can be seen in the supporting video where the Kinect was able to collect data for 75 evenly spaced points.

C. Experimental Design

The research team investigated whether the physical robot surface the author prototyped could assume the five spatial configurations offered in the simulations with an acceptable level of precision in its movements. Via smooth actuation of the motors driving the three tendons on the prototype, the physical configurations were achieved.

The research team then tested each configuration and its smoothness of movement from a "position of rest" (A) to the prescribed configuration (B, C, D, and E) by observing the motion. These motions can be seen in Appendix A3 "Video: Design and Characterization of a Novel Continuum Robotic Surface." Once each configuration was achieved, the author used the Kinect to capture the configuration of the three-dimensional location of each marked point on the surface. This experimental data was then compared to the three-dimensional location of the surface in the simulation.

D. Results

When observing the transition of the space-making robot surface between each configuration, the author found that the design quite successfully allowed for smooth transitions, regardless of the start and end configuration. The author also noted from the observations that the physical prototype convincingly assumed the desired configurations (Fig.5, bottom row) that were also achieved in the simulation (Figure 4, top row).

Configuration	Standard Deviation of % Difference	Mean Percent Difference (%)
A - Rest	2.759	4.24
B - Strong Bend	9.787	8.36
C - Soft Bend	20.968	15.72
D - Twist	17.406	29.61
E - Angled	18.802	14.46

Table 2. Summary of results

In order to compare the physical experiments to the simulation, the research team calculated the percent error between the experimental, Kinect-captured three-dimensional locations of the marked points and the corresponding points in the simulation. Table 2 summarizes the results of the experiments versus the simulations for the five configurations. A smaller standard deviation of the percent difference across the surface indicates a higher degree of consistency in relative positions, meaning the robot surface prototype was able to achieve the relative shape. The mean percent different indicates the average level of difference between the location of the simulated and physical surface robot with a lower percent difference being preferable.

VII. DISCUSSION

It was clear from observations during the testing of each configuration, and from deviations between the measured configurations and simulated configurations, that the surface was able to reasonably reconfigure itself to match the expected simulation configurations. For the (A) rest configuration, the simulation matched the experimental data with a high level of precision. For configurations (B), (C) and (E), the experimental data was within a reasonable range of precision. The higher-average percent error and standard deviations seen for configuration (D) twist is likely attributed to the fact that, for (D), the robot was actuated with a single tendon rather than two tendons (where one tendon would be less actuated) to better conform to the author's expectations. This can be improved by 1) updating the simulation mathematic model to take the rigidity of the material into account and 2) cutting some materials off the foam panel surface with carefully designed patterns to allow the tendon-driven motion to happen more smoothly.

Across the five configurations, deviations are likely caused in part by the Kinect's depth measurement error of anywhere between a few millimeters to 1 cm [11]. Additionally, deviations can be attributed to the kinematic model not accounting for the materials properties of the foam, variances in the movement caused by the rigidity of the collars, and the nominal deformities in the surface due to repeated bending. More sophisticated models would be required if we sought high accuracy in this mode.

Beyond the physical structure of the space-making robot prototype, the author considered the mechanisms by which the robot may be controlled by humans and may interact with humans in a given environment. Thus, the author exploring the inclusion of touch sensors on the surface, transducers to enable haptic interaction, RGBD sensors to enable gesture commands, voice control, and other control mechanisms. The investigations on the interaction modes of this robot surface prototype are presented in Chapter VI.

In sum, the results suggest validation between the experiment and simulation configurations: the space-making robot surface prototype is able to reconfigure itself successfully to the five desired configurations (and implicitly many others), corresponding to the developed kinematic simulation. The experiment overall successfully validates the novel concept of a surface robot as reconfigurable, adaptive, and space-making.

VIII. FUTURE WORK

Future work involves investigating human-robot in a variety of design tasks, use case analyses, and user studies to iterate the design for successful human-robot interaction in various environments (Appendix D2 for More Space Typologies), including a fully autonomous vehicle interior (Figure 5).

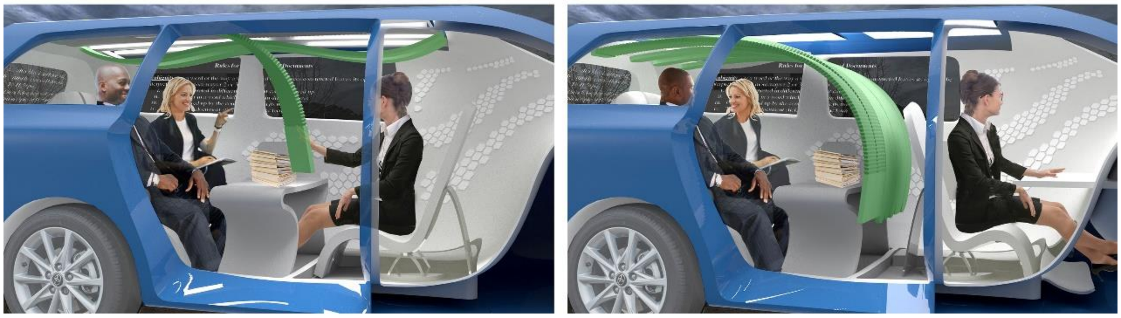

Figure 5. Space-making robot surfaces as envisioned inside an autonomous vehicle.

Future prototype iterations will explore varying degrees of thickness and alternative materials to better characterize how materials affect dexterity [8] and the capabilities of a surface robot.

Future work on the space-making robot surface also includes user studies involving human participants interacting with the robot. These studies aim to better understand the needs and expectations of a human inhabitant of an environment, such as a workplace. The author hopes that user studies will help us identify (a) which control mechanisms should be integrated into the robot, and (b) which tasks can be accomplished through the five robot "capacities." The author aims in these studies to demonstrate how surface robots can meet the needs of humans and extend the capabilities of the workplace environment (Appendix D2 for Workplace Scenarios).

ACKNOWLEDGEMENT

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SUMMARY FOR CHAPTER III AND IV

In CHAPTER III and CHAPTER IV, the author illustrated the design, engineering, and evaluation of two tendon-driven continuum robot surface mechanisms as space-making robot exemplars: one for build-scale applications (e.g., building skins or exterior walls.) and one for interior scale applications (e.g., embedded in ceiling of a room or autonomous vehicles.) These robot surfaces can be controlled as space envelops to reconfigure architectural spaces providing essential environmental affordances for different human activities.

Apart from contributing to the robotics community as novel continuum robot surface mechanisms, these two robot surfaces also serve as the potential space-making robot prototypes for the empirical experiments where users interact with these prototypes and self-report their opinions about and perceptions of these space-making robots. These experiments will serve as validations for our first hypothesis: "Users will perceive space-making robots as agents."

In next chapter (CHAPTER V), the author presents the user studies and experiments on the "perceived agency" of the interior-scale continuum robot surface. Both in-lab and online studies were conducted with the same, simple scenario where a participant co-works with the robot surface for a writing task. The robot surface was first embedded in the wall, and then bent down to reconfigure the functionality of the space by providing a writing surface.

CHAPTER V

ARE SPACE-MAKING ROBOTS, AGENTS? INVESTIGATIONS ON USER PERCEPTION OF AN EMBEDDED ROBOTIC SURFACE

(IEEE RO-MAN 2020; http://dx.doi.org/10.1109/RO-MAN47096.2020.9223532)

ABSTRACT

Abstract—Novel, "space-making" robots have potential to redefine physical space and the human activities occurring in it. Categorically distinct from many robots and far removed from humanoids, space-making robots are not objects in space, not anthropomorphic, not animal-like, not mobile, but instead, integral with the physical environment, embedded in or forming walls, ceilings, floors, partitions, vehicle interiors, and building envelopes. Given their distinctiveness, space-making robots offer a novel human-machine interaction. This paper investigates whether users perceive space-making robots as agents—artificial social actors characterized by the capacity for intelligence, recognition, and intention. Results of an in-lab experiment with 11 participants and an online, between-group experiment with 120 participants show that people attribute agency metrics of intelligence, intention, recognition, cooperation, collaboration, friendliness, and welcome to our reconfigurable robotic surface embedded in a wall partition. While space-making robots may become numerous in the built environment, our results are significant, moreover, for their broader implications for conceptualizing and designing human-machine interactions.

I. INTRODUCTION

The author's concept for the human-machine interactions of space-making robots—how people interact with them and how they are perceived by humans—is informed by two interrelated design-research paradigms: Human Robot Interaction (HRI) and Human Agent Interaction (HAI). These two design-research paradigms are reviewed in Chapter I: Introduction. Please refer to Chapter I for the details.

II. PREVIOUS RELATED WORK

The concept of space-making robot is based on the body of literature of "Architectural Robotics" and "Shape-Changing Interface." Please refer to Chapter I (Introduction) of this dissertation for literature reviews of "Architectural Robotics." Here below, the author will only review the literature of "Shape-Changing Interface."

A. Shape Changing Interface

Space-making robots and shape-changing interfaces [1] are both characterized by their capacity to physically reconfigure. However, many shape-changing interfaces are designed specifically for communicating information to users (e.g., physical information displays) and offering dynamic affordances (e.g., shape-changing buttons) [2], whereas space-making robots shape the spatial envelope and, as a consequence, the human activities within it. Future work in shape-changing interfaces will reportedly expand, interestingly, to architectural applications [2],[3], user experiences [2],[4], and user perceptions [2], all of which would converge further this classification of interfaces and space-making robots. In this light, the investigation reported in this paper represents the frontier of shape-changing interface research by investigating users' perception of agency in an architectural, space-making interface.

III. USABILITY STUDY

To investigate the research question, a space-making robot prototype is employed that was previously developed by the authors [5],[6]. This space-making robot is a tendon-actuated, continuum robot surface (Figure 1). The core of the robot surface is a 2-inch-thick foam panel banded by six thin, plywood collars (including two end-pieces) as armatures for 3D-printed guides through which three tendons are threaded, lengthwise. Motors mounted at the top of the surface wind the three tendons to reconfigure the surface into five different configurations as reported in [5]. The potential applications for this technology (e.g., reconfiguring spatial envelope and functionalities) are presented in our previous work [6].

To eliminate usability issues, a qualitative pilot study was conducted with 12 university students (ages 18-32, 4 FM, 8 M) asked to perform a writing task with the robot surface where experimenters controlled the surface for them, and provide feedback (Figure 1) based on two questions: 1) what their general impression of the technology are and 2) what they think should be improved for this prototype. The study was IRB approved and participants signed a consent form for video and audio release. Participants identified the following usability issues: a more rigid surface is preferred for the work surface; the worksurface was not sufficiently stable for work activity; and participants wished for a more refined interaction and prototype. The prototype was modified accordingly, and the improved prototype was used for the experiments described.

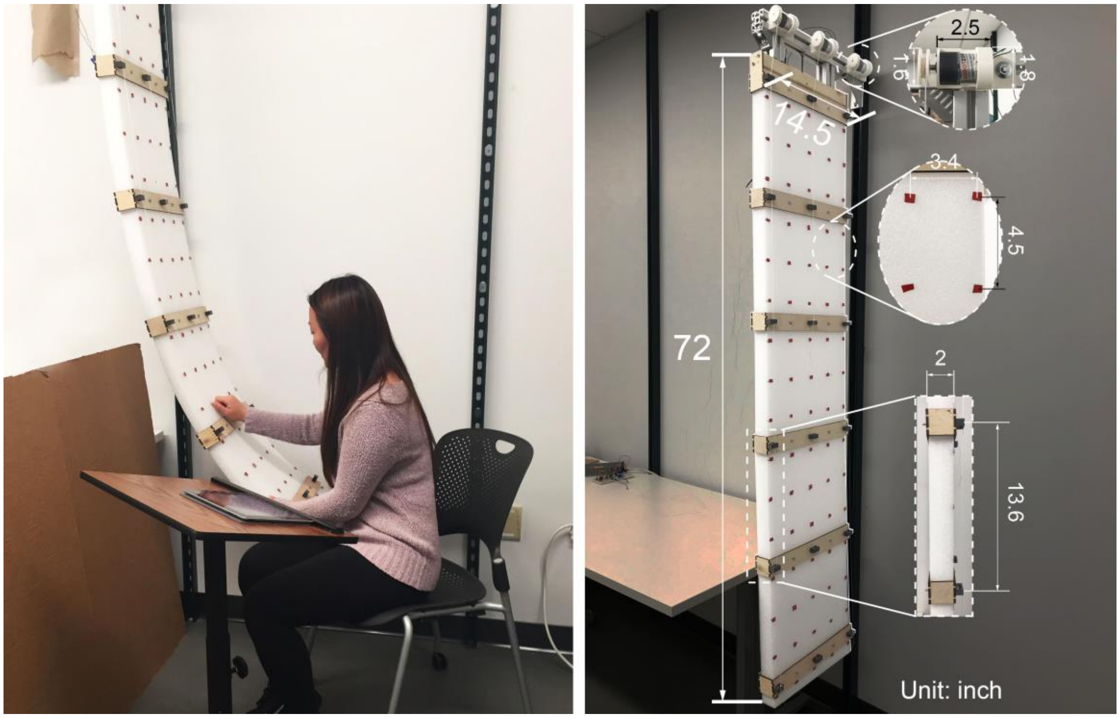

Figure 1. Robot surface (right) and photo from pilot study with user (left).

IV. IN-LAB EXPERIMENT

If a robot were to react as if it was understanding human needs, will it be considered to have agency? Our hypothesis is that users will perceive more agency from space-making robot surface through the automated, carefully designed movement of the robot surface, compared with user-controlled robot surface movement. The manipulated variable here is "robot surface movement" having two levels: the automated (simulated through WoZ (Wizard of Oz) [7] by experimenters), carefully designed (following the "Dynamic Movement Protocol" as described below) robot surface movement for the treatment group; and the fully user-controlled robot surface movement for the control group. For the treatment group, trajectories were designed that might trigger users' perception of robot agency [8] during a simple work task. Inspired by previous work in nonhumanoid robot movement design [9],[10], the authors designed and proposed the robot surface's "Dynamic Movement Protocol."

A. Task and Possible Scenario

In a room with only the wall-embedded robot surface and a chair (Fig. 2), a person is asked to copy a short paragraph on copy paper. This person might wish for a table or some other suitable writing surface, but there is none offered by the room; that is, until the embedded robotic surface provides one. While in motion, bending downward, the robotic surface pauses, permitting the user to recognize its hard surface as suited to the task. The user might consider this robot's affordance and may inspect it further. When the user moves closer, the robot surface adjusts its position subtly as a cue, and gently rests on the participant's lap to provide a writing surface. The user copies the paragraph easily; the robot surface then rises automatically, allowing the user to stand and leave the room.

B. Experiment Design and Environment Setup

The purpose of this experiment is to probe user perception and reaction to the autonomous (simulated by WoZ control) robot surface's behavior which traces our Dynamic Movement Protocol. Again, our hypothesis is that people will perceive more agency from the robot surface through the automated, carefully designed robot surface movement. Results of this in-lab experiment can help us improve our movement protocol and experimental design, based on user feedback. The authors used Likert items to measure subconstructs of "agent" (based on prior literature) and then asked three open-ended questions probing the reasons behind user perception and reaction. Each trial was video recorded for further analysis. The experiment took about 20 minutes for participants, each compensated with a $7 USD gift card. The study was IRB approved and participants signed the consent form for video and audio release before the study.

Ten college students (ages 19-34, 7 FM, 3 M) and one mature adult (59, FM) participated in this between-group experiment with random assignment: 6 in the treatment group and 5 in the control group. As per the scenario, for the in-lab experiment, participants were asked to copy a short paragraph on copy paper in a room with the wall-embedded robot surface and a chair only (Figure 3). For the treatment group, Experimenter A (Figure 3), situated behind a one-way window, remotely controlled the robot surface behavior tracing the Dynamic Movement Protocol simulating autonomous robot movements for the participants (as per the Wizard of Oz technique [7]). For the control group, the remote controller was given to the participant to fully control the robot behavior. The trials were video recorded.

After completing the task, participants were asked to answer the survey (Table 1). For participants in the treatment group only, a semi-structured interview was conducted by Experimenter B (Figure 3). The interview questions were: *(1) What did you think was happening when you saw the robot surface move? (2) Assuming the robot functioned properly, how did you interpret the robot surface's movement? (3) Do you consider the robot surface to be an intelligent agent, and why?*

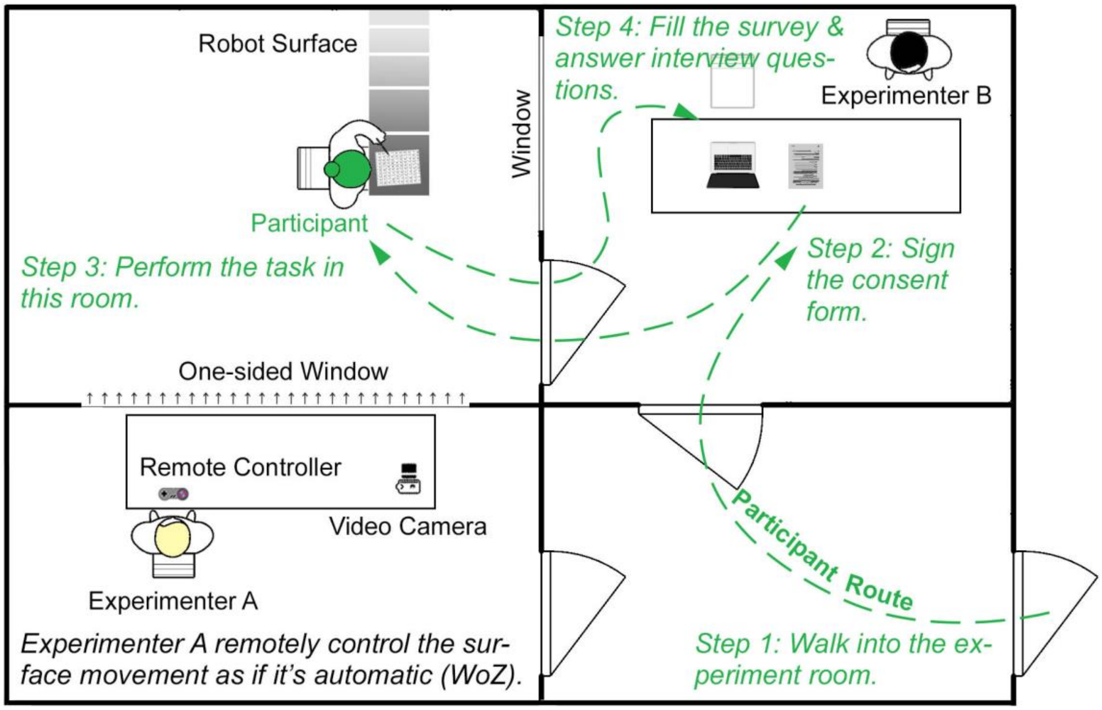

Figure 3. In-lab experiment procedure diagram and environment setup.

C. 5-Step "Dynamic Movement Protocol" (see Appendix A4 and Figure 2)

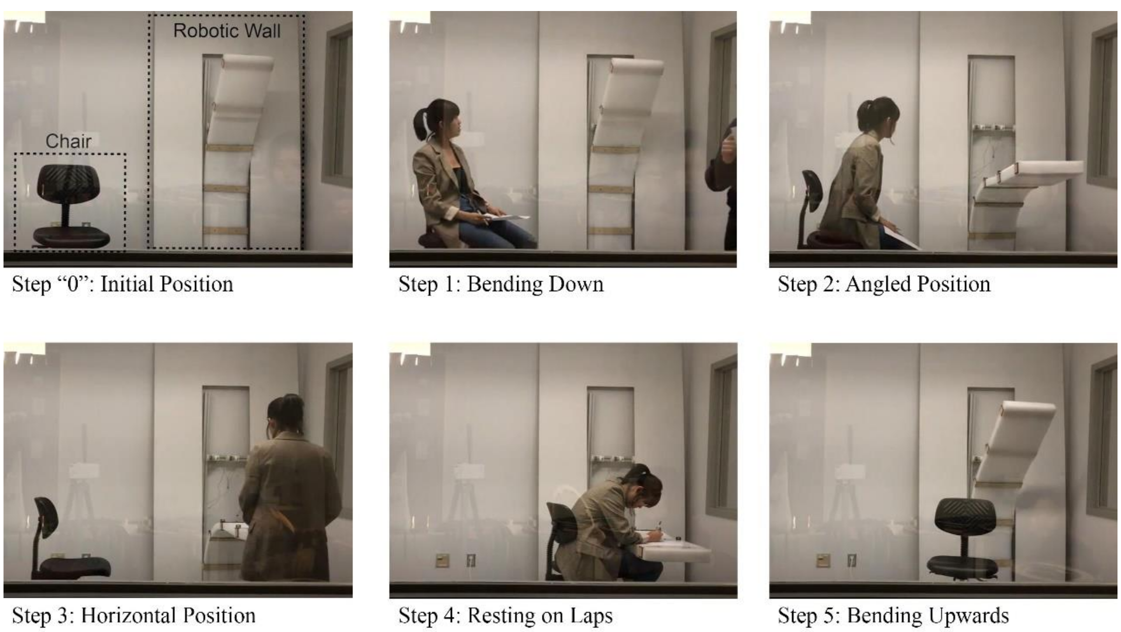

Figure 2. Dynamic Movement Protocol Diagram.

Step 1: When the user begins looking for a suitable worksurface, the wall-embedded robot surface, initially in an upright position, bends down automatically.

Step 2: Then, the robotic surface pauses for 3 to 5 seconds after reaching an angled position at 15 degrees above the horizontal plane. This movement may elicit a user's attention and increase the robot's perceived "politeness" [7],[9].

Step 3: Subsequently, the robotic surface bends gently downward until it is horizontal—a prompt for user engagement [7],[9].

Step 4: When the user moves close enough and has her/his lap beneath the robot surface, the robot surface will subtly rest on her/his lap. This is the step where the robot fulfills it functionality [9].

Step 5: Finally, when the user finishes copying the paragraph and tries to stand up, the robot surface will automatically bend upwards to its initial, vertical, wall-embedded position.

D. Survey Questions (Table 1)

Based on our definition of an "Agent" following the literature [9],[10],[11],[12], the authors measured people's perception of intention (Q5, Q9), recognition (Q4, Q7, Q14), and intelligence (Q2, Q6, Q8) of the robot surface. The authors also probed users' social perception [8],[11] of the robot surface by asking questions about perceived cooperativeness (Q11), friendliness (Q13), welcome (Q16), and collaboration (Q17) which were borrowed and modified from a validated "Social Perception" sub-scale [13],[14]. These 7-point Likert items were evaluated and iterated by three HRI experts for content and face validity several times. Here, the authors are by no means developing a validated scale for measuring "Agent Perception" (and there is not one yet), although the internal consistency of these 12 items were found to be very high (Cronbach alpha= 0.91). The authors ask questions directly about the subconstructs we aimed to measure [10].

Q2: The robotic surface seemed to think when doing something for you.
Q4: The robotic surface seemed to recognize that you needed a hard surface to write on.
Q5: The robotic surface didn't intend to do anything for you.
Q6: The robotic surface had no intelligence at all.
Q7: The robotic surface seemed to understand your needs.
Q8: The robotic surface was acting deliberately.
Q9: The robotic surface was trying to provide a work surface for you.
Q11: The robotic surface was trying to be cooperative.
Q13: The robotic surface was trying to be friendly.
Q14: The robotic surface didn't recognize what you needed to do.
Q16: The robotic surface was trying to be welcoming.
Q17: The robotic surface was collaborating with you.

Table 1. Survey questions for subconstructs

E. Results and Findings for the In-lab Experiment

With only 5 and 6 participants respectively in the control and treatment groups (because of the pandemic, which closed our in-lab study prematurely), the survey results were limited. The findings presented below are mostly based on the interview results and video recorded observations.

Firstly, participants, irrespective of being assigned to the control or treatment groups, have very different reactions as presented in Table 2: 6 participants used the robot surface as the writing surface, 4 participants used interior walls or windows as writing surfaces, and 1 participant used his lap. This suggests that our Dynamic Movement Protocol could be improved to account for different user reactions; this improvement was made for the online experiment reported in the next section (see, also, [10] and Appendix A4).

	Using **Robot Surface** as Writing Surface	Using **Wall or Window** as Writing Surface	Using **His/her Laps** as Writing Surface
Treatment Group	Participant 1, 4, 10	Participant 2, 8	Participant 6
Control Group	Participant 3, 9, 11	Participant 5, 7	

Table 2. Reactions of Different Participants in Treatment and Control Group (Deeper Blue Represents More Participants; Grey Represents No Participants)

Secondly, participants do perceive intention, recognition, or intelligence out of the WoZ controlled movement, although some of them did not use the robot surface for the writing task because it did not seem OK for writing. This may suggest that a user's failure to use the robot surface does not necessarily predict her/his positive perception of intention, recognition, or intelligence. For instance, more than one user offered that she/he understood "the robot surface was providing a table for me," but didn't use it because "the material looked soft."

Thirdly, participants who perceived intention, recognition, and intelligence of the robot surface may not attribute these characters to the robot, as they suspected someone else was controlling the system. Participant 4 was an HRI researcher who said, "that window might be a one-way mirror." Participants in this mindset (participant 4 and 8) may give low scores to most of the survey items, as this participant did.

Finally, in our interview, four out of the six participants perceived the robot surface as "accommodating," "providing a table," or "having done the right thing." In the survey responses from the 11 participants, there is an average of about 2 points higher for most of the 7-point Likert items from the treatment group than the control group. This may suggest that our experiment design in general works, and our Dynamic Movement Protocol fulfilled its purpose sufficiently to trigger user's agency perception.

V. ONLINE EXPERIMENT

(Appendix A4 and A5 for Video Narratives)

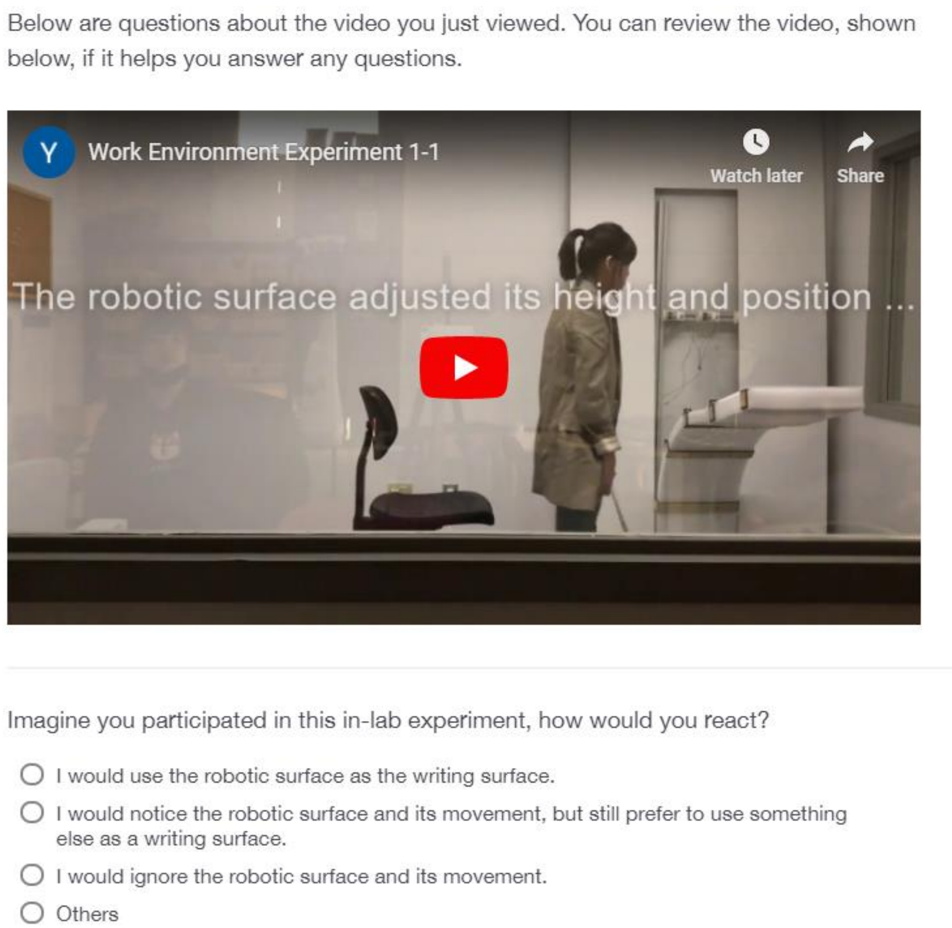

Figure 4. A screenshot of the online survey.

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-minute (treatment group) or 12-minute (control group), IRB approved study. Following prior HCI research ([10],[15]), our online studies asked participants to imagine themselves in the interactive experiment settings to then answer interpretive questions. With rigorous exclusion methods, participates can vividly transport themselves into the experiment settings and provide valid feedback of their perceptions, emotions, etc. [10],[15].

A. Survey Design (Appendix B for Complete Questionnaires)

Figure 4 shows a screenshot of the online survey. In the online surveys, a video narrative of the in-lab protocol (treatment group in Appendix A4; control group in Appendix A5) was played for participants who were asked to imagine participating in the in-lab experiment and to answer questions on how they would react, and why. Then, online participants were asked to answer survey questions as offered in Table 1. Finally, for the treatment group only, the same three open-ended questions asked of the in-lab group were asked.

B. Results and Findings (Statistics in APA Style)

The authors screened the data and excluded two observations in the control group because their responses for questions before the Likert items were not question-related. 118 observations remained left for analysis. Results are as follows: Q2, Q6, and Q8 have an acceptable internal consistency (Cronbach alpha= 0.79) measuring perceived intelligence; Q4, Q7, and Q14 also have an acceptable internal consistency (Cronbach alpha= 0.72) measuring perceived recognition; and Q5 and Q9 have a significant correlation ($r_s(58) = 0.61$, $p < 0.001$) measuring perceived intention. Figure

3 presents the descriptive statistics for each subconstruct, calculated based on values from 1 (strongly disagree) to 7 (strongly agree). The coding for the each subconstruct in Fig.5 with the corresponding survey question number is: “Intel” for Perceived Intelligence (Q2, Q6, Q8), “Rec” Perceived Recognition (Q4, Q7, Q14), “Inten” for Perceived Intention (Q5, Q9), “Coop” for Perceived Cooperation (Q11), “Col” for Perceived Collaboration (Q17), “Fri” for Perceived Friendliness (Q13), and “Wel” for Perceived Welcome (Q16). Values for Q5, Q6, and Q14 are reversed before calculation.

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 a general perception difference around “somewhat disagree” and “somewhat agree” for the participants in different groups. In addition, SD values in treatment group are all smaller than the ones for the control group, with the differences ranging from 0.18 to 0.51. This suggests that participants’ opinions converge better in the treatment group than in control group.

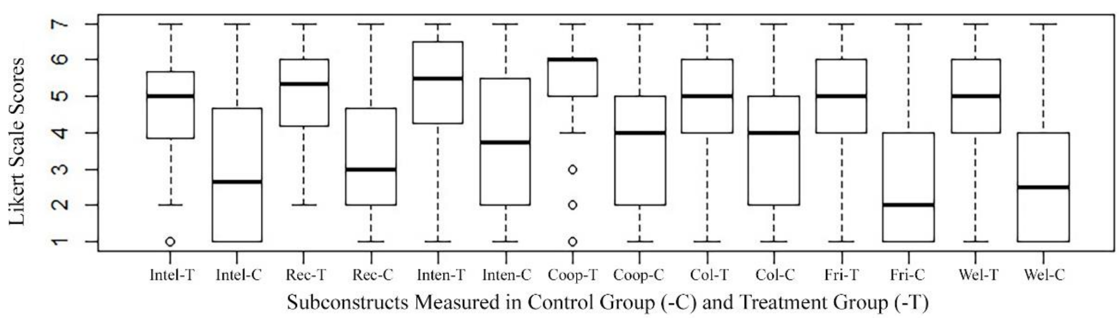

Figure 5. Online Experiment Results: Descriptive Statistics

A Kruskal-Wallis H test was performed to explore “perceived intelligence” (mean values of Q2, Q6, and Q8) as “group assignment of the participants” (treatment or control group). There is a statistically significant difference between the perceived intelligence and participant groups (χ 2 (1, N = 60) = 21.72, p< 0.001) with a mean rank of "perceived intelligence" of 4.69 for treatment group and 3.09 for control group (mean ranks presented in Fig.3). The authors did the same test for all other subconstructs, and the results are presented in Table 3. The extremely small p-values suggest that participants in the treatment group did perceive more intelligence, recognition, intention, cooperativeness, collaboration, friendliness, and welcome from the robotic surface than the participants in the control group.

Subconstruct	**Kruskal-Wallis H Test Results**
Perceived Intelligence	χ 2 (1, N = 60) = 21.72, p<0.001
Perceived Recognition	χ 2 (1, N = 60) = 36.70, p<0.001
Perceived Intention	χ 2 (1, N = 60) = 18.51, p<0.001
Perceived Cooperativeness	χ 2 (1, N = 60) = 21.29, p<0.001
Perceived Collaboration	χ 2 (1, N = 60) = 12.51, p<0.001
Perceived Friendliness	χ 2 (1, N = 60) = 20.79, p<0.001
Perceived Welcome	χ 2 (1, N = 60) = 20.16, p<0.001

Table 3. Kruskal-wallis h test results

For both the treatment group and control group data, the author used Spearman's correlation test to investigate the correlations pair by pair for the three subconstructs: "intelligence," "intention," and "recognition." The results are presented in Table 4 and Table 5. These results suggest strong correlations between each of the two subconstruct since the critical Spearman's correlation value for the significant level of 0.01 is ρ_c= 0.238, which is smaller than any of the coefficients presented in Table 4 and Table 5.

Answers from the three open-ended questions further explained the reason behind participants' responses. 43 of the 60 treatment participants (72%) considered the robot surface intelligent, and at least 38 of them said it was intelligent because it "recognized what I need," "understood where my lap was," or "sensed I was in the room," and then "formed a desk," "adjusted itself per individual," "acted accordingly," etc. In other words, *the reasons for users perceiving the robot surface as intelligent is that the robot surface recognized the situation and then performed an intentional and helpful act.* There are 15 participants who did not think it was intelligent: 6 of them did perceive its intention or recognition but argued "it was programmed to do so"; 4 of them said it was not intelligent because "an experimenter was controlling it"; 5 of them reported its actuation velocity didn't match their expectations. Finally, there are 2 participants not sure if it was intelligent as they suspected "it was controlled by someone else."

Treatment Group	Intelligence	Recognition	Intention
Intelligence	1.00	0.790 (> 0.238)	0.664 (> 0.238)
Recognition	0.790 (> 0.238)	1.00	0.678 (> 0.238)
Intention	0.664 (> 0.238)	0.678 (> 0.238)	1.00

Table 4. Spearman Correlation Coefficients Matrix for Treatment Group

Treatment Group	Intelligence	Recognition	Intention
Intelligence	1.00	0.810 (> 0.238)	0.797 (> 0.238)
Recognition	0.810 (> 0.238)	1.00	0.725 (> 0.238)
Intention	0.797 (> 0.238)	0.725 (> 0.238)	1.00

Table 5. Spearman Correlation Coefficients Matrix for Control Group

VI. DISCUSSION

Both our qualitative and quantitative results from the online experiment suggest that people do perceive intention, recognition, and intelligence in the robot surface, a space-making robot reconfiguring the space from "a room without worksurfaces" to "a room with a worksurface"—a change in room functionality. The authors would moreover argue that the "automated, carefully designed space-making robot movement" can be a key factor influencing users' perception of human-(space-making) robot interaction, as manipulating this variable in our online experiment was associated with users' perception of the seven subconstructs (intention, recognition, intelligence, cooperativeness, collaboration, friendliness, and welcome), all changed from negative (around "somewhat disagree") to positive (around "somewhat agree"). This change in perception can be attributed to multiple aspects of the WoZ control of robot's behavior, including its dynamics, speed, and trajectory: All aspects warrant further investigation.

Based on qualitative results from both in-lab and online studies, there is a strong internal consistency and an underlying narrative among users' perception of intention, recognition, and intelligence. Our statistical analysis shows that all items for these three subconstructs together had strong internal consistency (Cronbach alpha=0.89 for treatment group, and 0.92 for control group). The narrative beneath this correlation is as follows: users believed that the robot surface recognized their situational needs and, in response, performed an intentional and helpful act. As such, participants considered the robot surface as intelligent. This means that even though the space-making robot is not anthropomorphic, not animal-like, not mobile but, instead, embedded in the spatial envelope of the room, as long as the robot's behavior (i.e. movement) responds to a person's intentional stance [12], a person will likely perceive it as a "logical agent" [12] with intention, recognition, and intelligence.

Our quantitative results show that people did perceive the robot surface as trying to be cooperative, collaborative, friendly, and welcoming with a mean rank of 4.93. Although more empirical studies are needed to conclude that "space-making robots are social actors" [16], our study does suggest that the designed, WoZ controlled, and dynamic movement of a space-making robot can be perceived by people as social.

VII. LIMITATION

There are a number of limitations to our findings.

Firstly, most of the experiment data, except for the video recordings from the in-lab experiment, were self-reported, which may pose validity problems.

Secondly, the authors did not insert "attention checkers" within the online questionnaire. However, we did preselect reliable participants (Master Workers only), pay workers a higher market-rate reward, and use multiple screeners for the data as recommended by the literature for MTurk experiment validity [15]. Our online survey was conveniently short, taking only, on average, 600secs for the treatment group and 377secs for the control group (since the latter had three less open-ended questions).

Thirdly, due to the pandemic, the authors were forced to move the in-lab experiment to an on-line platform. Although former studies found that MTurk workers "buy into interactive experiments and trust researchers as much as participants in lab studies" [15], it is still possible that "ecological validity" may have been sacrificed [10].

Finally, the 12 Likert items used in the two studies cannot be characterized as a validated scale. Although the authors tried their best to improve the validity of these items through literature backup and expert evaluations, it is not the focus in this paper to develop such a scale. Nevertheless, these 12 items did achieve high internal consistency and may serve as the raw material for researchers who want to develop a validated scale of "Perceived Agency" in the future.

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SUMMARY

In this chapter, the author presented the processes and results of two experiments, investigating perceived agency through established metrics of intelligence, intention, recognition, cooperation, collaboration, friendliness, and welcome. Both the qualitative and quantitative results from the in-lab and online studies strongly suggest that people do perceive intelligence, intention, recognition, cooperation, collaboration, friendliness, and welcome from the dynamic, designed, and autonomous movements of the continuum robot surface embedded in the wall. Thus, these evidences support that people do perceive space-making robot as agent, and more specifically, through the carefully design robot movements. Hypothesis 1 is validated.

Although space-making robots can be designed as agents as people do perceive such interactive and adaptive space-making robots as agents, it does not mean that space-making robots should always be AI-embedded or designed as agents regardless of different contexts, circumstances, and situations in everyday life. For instance, users may prefer space-making robots to be agents in some situations, but only tools in other situations. In the next chapter, the author investigated people's preference for different interaction modes of space-making robots in different tasks and scenarios. The author also probed why users prefer AI-embedded interaction modes (which can evoke users' agency perception) for certain tasks, but fully user-controlled interaction modes for others. The research results help designers to decide when to design space-making robots as agents, and when not to.

CHAPTER VI

GIVING SHAPE TO WORKING LIFE: USER PREFERENCES FOR INTERACTING WITH ROBOT SURFACES IN COMPACT WORKING ENVIRONMENTS

ABSTRACT

In this chapter, the author reports on user preferences for different interaction modes when interacting with space-making 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. The author envisions 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 (or "scenarios") over the duration of the task. The author 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. This research informs the design of increasingly complex, spatial human— "space-making robot" interactions in everyday life, especially under what scenarios users may prefer AI-embedded partner-like interactions with robot surfaces and under what scenarios users may prefer to use them as simply tools.

I. INTRODUCTION

As the author presented in former chapters, partner-like space-making robots (robot surfaces) can reconfigure working environment and support different work activities. *However, the author believes that although space-making robots can be perceived and designed as agents, users may prefer different human— "space-making robot" interactions in different scenarios and tasks: users may prefer space-making robots to be agents in some scenarios, but only tools in other scenarios.* To provide a sense of robot surface behaviors and applications, the author present (in Table 1) five "scenarios" for the use case of designers working in a micro-office. Such 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 presented in Chapter II. 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, the authors tested with users the question, what kind of human—robot-surface interactions would users prefer most in these different scenarios, and why? For each scenario, user preference of five different interaction modes were investigated: some of them can enable users' agency perception of space-making robots, and some of them cannot. For screen-based and other relatively structured tasks, researchers have offered general design guidelines for AI-embedded interface design [1],[2],[3],[4],[5]; but in the wild frontier of spatial human—robot-surface interactions, such questions demand considerable attention.

Scenario	Conceptual Diagram	Task Description by Scenario
Scenario 1: *Note Taking*		In the morning, you and your client come into your office. You sit down together and discuss the plans for a project. During the discussion, you want to take notes for some important points. So, you would like the robot surfaces to bend down and provide you a tablet for notetaking.
Scenario 2: *Shape & Atmosphere Simulation*		You and your client are discussing the design of a product. You want the product's case to have a wavy pattern, as if sea waves. So, you would like the robot surfaces to simulate wave-like patterns to help make clear your design intention.
Scenario 3: *Space Division*		You and your client are in a discussion. Suddenly, you receive an urgent email requiring your immediate attention. You need privacy to answer the email, so you want a private space. You want the robot surfaces to bend down, dividing space into two parts for your and your client's private working.
Scenario 4: *Presentation*		You want to present some of your design ideas and sketches to your clients. So, you would like the robot surfaces with bendable screens to bend down, providing you a big screen for presentation.

Scenario 5: Body Support		After a long day of work, your clients finally have left. You feel tired and want to lean upon a soft body support for a rest. So, you would like the soft robot surface to bend down and support your back with a ergonomic and comfortable curvature.

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

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.

To address this research question, the authors 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 five scenarios ("user enactment" [6] introduced by Odom, et al. 2012) 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 for the differences.

II. RELATED WORKS

This 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 the 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. For the *architectural robotics* and *shape-changing interfaces*, the author has reviewed the key literatures in Chapter I and Chapter V. Here, the author will only review *Computer-Supported Cooperative Work* and *Robots that Work with Humans.*

A. Computer-Supported Cooperative Work

CSCW communities have been exploring computer-supported cooperation for collaborators in different locations through groupware [7],[8],[9],[10],[11] mixed reality[12],[13], and virtual reality [14],[15]. The work in this chapter could arguably be characterized as an exploration of "computer-supported cooperative work environment" in that collaborators in the scenarios (Table 1) are working together in a computer-supported office with robot surfaces. The CSCW literature provided the author many insights of the inter-human cooperative working process such as "face-to-face gestural interactions" [16] and "workspace informal communications" [17],[18]. These insights were useful when designing interactions for the partner-like robot surfaces (Table 1). This work is novel for CSCW research in that the co-workers in the 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.

B. Robots that Work with Humans

This research benefits from the well-established body of literature on human-robot interaction [19], social robotics [20],[21],[22],[23] and the ubiquity of robots [24],[25],[26] drawing inspiration especially from research literature [27],[28],[29] focused on applications of robots in homes [30],[31],[32], and healthcare [33]. Furthermore, this research draws inspiration from research in robotics focused on applications that influence how human beings approach tasks in work environments [34],[35],[36]. 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. The author reports here on how robot surface interactions might be made functionally effective, socially supportive, and emotionally encouraging to users in a confined workspace through the user-preferred interaction modes for different scenarios.

III. PHYSICAL PROTOTYPE IN-LAB STUDY

For this study, the author invited to the 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.

A. Study Design

For this exploratory, qualitative study, the 12 designers were asked to evaluate human—robot-surface interactions in the 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” [37], the authors 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 through “user-enactments.”

B. User Enactments and Semi-Structured Interviews

The author conducted “user enactments” [6] 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” [6]. 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 the lab fashioned as a compact, micro-office environment with chair, table, shelves, and a computer. In this office setting, we added a functional, button-controlled robot surface prototype (presented in Chapter IV) of our design measuring. 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), The author allowed the participants to experience both the physical setting of a typical office together with the intervention of the robot surface. After participants finished all the five tasks, semi-structured interviews were conducted probing their general impressions of, comments on, and suggestions for this new technology.

The continuum robot surface prototype, as presented in Chapter IV, has five controllable configurations: "rest position," "soft bend," "strong bend," "angled," and "twisted." The robot surface configuration used in this user study is initially the "soft bend" (shown in Figure 2) which produces a bend slightly upwards, providing a working surface for reading or writing. In this 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 [38].

C. Procedure: Study Protocol and Interview Questions

First, the experimenters introduced this robot surface prototype to the participant by verbally describing its structures, functions, and potential applications.

Second, the experimenter 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.

Third, the experimenter 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 and Appendix A6 (Video: Six Different Interaction Modes Illustrated Through Scenarios).

Fourth, the experimenter 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 2). Using the "Wizard of Oz" technique [38], all five interactions were simulated, one by one, for the participant while he/she is performing the given task. The experimenter then asked the participant to choose her/his most preferred interactions or propose new interactions.

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.

Sixth, this 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?

- Question 3: What other use cases can you think of for this technology?

D. 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. 3 shows how many times each of the five interaction modes was rated as the favorite one for each scenario by participants. The data is color coded with deeper blue representing more votes.

Interaction Mode	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Button	1	1	4	2	0
Voice Command	0	3	0	3	2
Human Activity Recognition	6	2	2	5	5
GUI	3	5	3	4	2
Proximity Sensor	1	0	4	0	2

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

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 the authors, capture what was communicated repeatedly by two or more participants.

- 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).

- 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).
- By capturing data coming with human body gestures as a control mode, more comfortable body support could be provided (Participants 5, 8, 11).
- It is “discreet rather than distracting” to the user (Participants 7, 10).
- 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).

2) Participants’ Feedback on “Human Activity Recognition” (Interaction 3)

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:

- This interaction is relatively quiet, discreet, and not distracting (Participants 2, 5, 6, 10).
- This interaction offers user control with enough many options (Participants 2, 12)
- 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.

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:

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

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).

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). The authors 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.” The authors believe these are all inspiring ideas for designing human-surface interaction.

IV. FINDINGS AND DISCUSSIONS

We now consider how our results provide insights for robot surface interaction design in a compact, interactive working space, and inspire future research for complex human— “space-making robot” interactions including those that are AI-embedded and can be perceived as human-agent interactions.

A. 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. According to the user-perception experiments in Chapter V, these interaction modes could potentially enable users' agency perception of the AI-embedded space-making robots. User-controlled interactions refer to the interactions where users give direct command to the system.

First, users prefer AI-controlled modes for the simpler scenarios (e.g., Scenario 5 "body support") which requires 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).

Second, 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).

Finally, 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 human-surface interactions.

V. FUTURE RESEARCH

Because of the limited time that could devote to each participant-session in the lab study and the limited number of interaction modes participants could remember when making a choice, the author selected with hesitation to not include semi-autonomous interaction modes as an option in our studies. Interestingly, users did not propose any semi-autonomous interactions either in the study. The author intends to pursue this research direction in the future as further user studies being intensively conducted with a full-functioning system of multiple robot surfaces [39]. The author will explore user preferences of semi-autonomous interfaces with built-in verification steps [2],[5], direct manipulation constructs [3], and predictable AI behaviors [1]. The author believes a seamless integration of AI-controlled, user-controlled, and semi-autonomous interactions can be the next step of human— "space-making robot" choreography in an interactive space.

Informed by these findings, the author 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 the author 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. Participants with different backgrounds will be invited 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).

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SUMMARY

In this chapter, the author investigated in what scenarios and tasks users may prefer AI-embedded interaction modes (which can evoke agency perception of space-making robots) when interacting with space-making robots. The interaction modes investigated include Buttons, Voice Control, Human Activity Recognition, Natural Language Processing, Proximity Sensor, and Graphic User Interface. The study results suggest that people may prefer agent-like interactions with space-making robots when the required robot controls for the task are simple, hard to specify, or preferred to be discreet.

Although the study results are preliminary, it does confirm the author's hypothesis that the design decision of designing space-making robots as agents should be made case by case. Nevertheless, user preference may not be the only factor that should be considered for such design decisions, and further investigations on the agency-based space-making robot design are needed.

CHAPTER VII

CONCLUSION

I. CONTRIBUTION OF EACH CHAPTER

Explorations of the design paradigms and frameworks for interactive built environments are important academic endeavors, especially today when interactive installations, robotic architecture, and smart cities are becoming more and more prevalent and inevitable in our lives [1],[2],[3]. To establish an evidence-based, validated design paradigm through a human-centered Research through Design (RtD) approach [4], the author needed to investigate users' perceptions of the interactive environment and its user interactions through empirical user studies [5]. To conduct such user studies, the author designed, engineered, and evaluated two space-making robots (which are an essential component of interactive environment) for space-making applications in different scales, including an application for the experiment scenario [6],[7]. At the core of this dissertation is the HAI-based design paradigm for space-making robots. To validate this paradigm, the author developed space-making robots for experiments; and to apply this design paradigm to design process, the author proposed the "pattern-based, design framework for designing collaborative environments" which was then validated through a design exemplar of a "partner-like working environment" [8]. As a conclusion, the author offers the key contributions of this research by subheadings which together offer a complete story discussing the research topic: how should we design space-making robots and their user interactions?

A. Theoretical Foundations for HAI-based Design Paradigm and Framework

In Chapter II, the author first proposed an HAI-based design paradigm for spatial, interactive artifacts based on the HRI and HAI literatures. Following this design paradigm, the author presented a pattern-based framework for designing interactive artifacts that are spatial and humanlike, such as space-making robots. In so doing, the author has explored how human-human interaction can be studied, analyzed, and translated into the interactions of people and space-making robots. As part of this framework, the author introduced three novel, translational strategies: Direct Mapping, Conveyed Mapping, and Space Agency. The author then presented a design exemplar of a "partner-like, collaborative space-making robots"—the design of a collaborative space-making robot for design activity—that served as a means to elaborate and validate the framework.

B. A Bio-inspired Continuum Robot Surface

In Chapter III, the author presented simulations and a working prototype of CompResS, a novel "compressed robotic surface." Unlike earlier robotic design efforts applied to the built environment, CompResS can be described as space-defining, controllable, and 2D reconfigurable. The author presented the core concept, design and realization of a physical prototype. The author found that, for four distinct, desirable, physical configurations, there was a strong match between our prototype and its ability to emulate these configurations. Finally, the author envisioned potential applications. CompResS offers a possible new frontier of exploration for robotics at the scale of the built environment.

C. A Tendon-driven Continuum Foam Panel as Space Agent

In Chapter IV, the author presented the design, kinematic model, simulations and a working prototype of a Space Agent, a novel tendon-driven robot surface for human environments. Unlike earlier robot design efforts applied to the built environment, robot surfaces like the Space Agent are space-defining, controllable, and potentially capable of augmenting human capabilities within a physical work environment. The author presented the core concept, design, and realization of a physical prototype. The author found that, for five distinct, "typological" configurations of the robot surface, there was a reasonable match between this prototype and its ability to emulate the modelled configurations. Robot surfaces like the Space Agent offer a new frontier of exploration for robotics applied to the built environment.

D. Space-Making Robots Can Be Perceived as Agents

Figure 1. Space-making robot surfaces in an autonomous vehicle.

Are space-making robots, agents? Based on the investigation reported in Chapter V, the author concludes that people do perceive the intention, recognition, intelligence, cooperativeness, collaboration, friendliness, and welcome of a space-making robot. Following the literature cited in Chapter V, these seven constructs encompassing the key aspects of what defines an "agent" (a logical agent [9] and a social actor [10]) served as metrics for arriving at this conclusion—that space-making robots can be agents. However, more empirical studies are needed for a more affirmative conclusion. While space-making robots may become numerous in the built environment (as in our vision for a smart vehicle interior, Fig.1), the conclusions reported here are significant, moreover, for their broader implications for conceptualizing human-machine interactions and probing notions of intelligence.

E. User Preference for Human— "Space-Making Robot" Interactions

Although space-making robots can be designed and perceived as agents, people may or may not prefer space-making robots being agents in different scenarios. In Chapter VI, the author offers insights into user preferences for space-making robots (shape-changing robot surfaces) with different autonomy levels in different working scenarios. The study results show that:

- Users prefer AI-controlled interaction modes for the simpler scenarios.
- Users prefer AI-controlled interaction modes for scenarios where human-surface interactions are supposed to happen in discreet, or a natural way with instant feedback.
- Users prefer AI-controlled interaction modes for the controls that cannot be easily specified by direct commands (such as the detailed curvature of the robot surface).

The "AI-controlled interaction modes" here refer to the interaction modes where the AI system automatically gathers information from the users, analyzes the data, and makes decisions on activating or reshaping the robot surface for users. This kind of interaction modes, according to our study results in Chapter V, may evoke users' agency perception of space-making robots.

More broadly, for design and HCI researchers, the research reported here contributes to the understanding of our future coexistence with robot and computer-embedded built environments, such as the smart, interactive micro-offices and micro-apartments that may become increasingly familiar typologies as society mass-urbanizes.

II. LIMITATIONS

There are several limitations of this dissertation:

First, the “agency perception” measure used in Chapter V for investigating users’ agency perception of space-making robots is not a validated scale. Although the author tried his best to improve the validity of these items with the limited time and resources, this may pose internal validity problems for this dissertation.

Second, due to the pandemic, the authors were forced to move the in-lab experiment to an on-line platform. It is possible that online studies may pose “ecological validity” problems to this dissertation.

Third, the experiments and studies of this dissertation focus on a specific kind of space-making robot, which is robot surface. Further studies are needed to investigate users’ perception of, interaction with, and preferences for other space-making robots (such as different kinds of architectural robotics installations) so that the agency-based design paradigm can be more generalized.

Finally, more on-site, empirical investigations on how users interact with agent-like space-making robots in different scenarios and contexts are needed so that design researchers may have a better understanding to the relationship between agent-like space-making robots and users. Better design framework and guidelines can be generated based on the on-site, empirical, and even longitudinal studies.

III. CONTRIBUTIONS AND POTENTIAL BROADER IMPACTS

A. A New Design Paradigm for Adaptive & Interactive Space-Making Robots

In this dissertation, the author proposed and validated a new design paradigm for adaptive and interactive space-making robots. Since space-making robots can be the basic robotic building components (e.g., robotic walls, ceilings, floors, partitions, interior or exterior installations, etc.), this design paradigm can be widely applied to the design of interactive and adaptive spaces, especially the compact spaces such as micro-offices (Figure 2), micro-apartments, autonomous vehicles (Figure 1), space capsules, etc. as mentioned in the "Introduction" section of this dissertation.

Figure 2. Reconfigurable Compact Office with Space-Making Robot Surfaces

B. A New Subfield for Human-Machine Interaction (HCI/HRI) Research

The author defined space-making robots and validated that they can be perceived and designed as agents, which are "rational agents" and "social actors" perceived through people's intentional stances. Thus, space-making robots are now social robotics, which means they can and should be investigated as socially interactive robots. This dissertation is a foundational work for the new research field of "socially interactive space-making robots," which is a subfield for HCI and HRI research.

C. Technical Contributions: Two Novel Continuum Robot Surface Mechanisms

In Chapter III and Chapter IV, the author presented the design, engineering, and evaluation of two novel continuum robot surface mechanisms: one for building scale applications and one for interior scale applications. These two mechanisms serve as two design exemplars and inspirations for future space-making robot design and research, and they can also be applied in many different contexts and spaces in our everyday life. For instance, the interior scale continuum robot surface can also reconfigure living spaces at smart home (Figure 3) and smart nursing home (Figure 4).

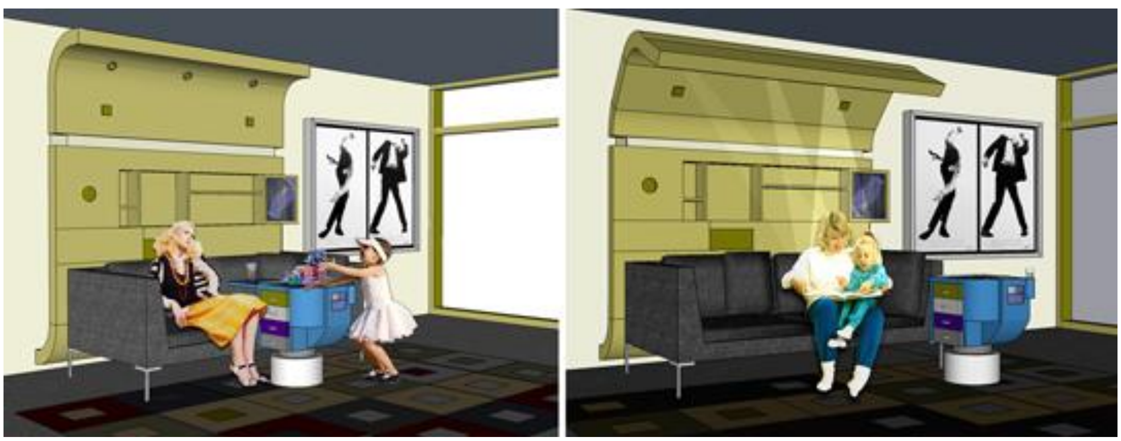

Figure 3. Robot Surface Envisioned in Smart Home

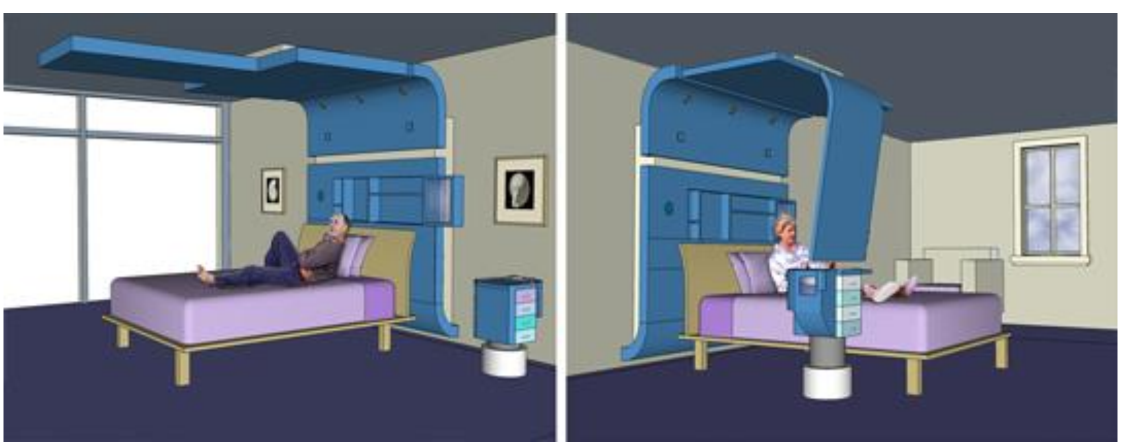

Figure 4. Robot Surface Envisioned in Smart Nursing Home

D. Broader Impact to Industry and Our Life

As shown in Figure 1, Figure 2, Figure 3, and Figure 4, space-making robots have many very promising applications in domains including healthcare, education, smart transportation, working environment, living environment, etc. Thus, adaptive and interactive space-making robots can have great impact on architecture industry, healthcare industry, autonomous vehicle industry, and many other industries related to smart homes, smart nursing homes, smart transportations, micro-apartments, space exploration, etc.

As space-making robots becoming more and more prevalent in our everyday life, our agent-like interactions with them and the surrounding adaptive built environments may change our behaviors, habits, lifestyles, workstyles, and even perception and conceptualization of the world around us.

IV. HOW SHOULD WE DESIGN SPACE-MAKING ROBOT?

According to the conclusion of Chapter V, people do perceive intention, recognition, intelligence, cooperativeness, collaboration, friendliness, and welcome from an interactive and adaptive space-making robot. More specifically, the experiments' results support that people perceive space-making robots as both "rational agents" and "social actors" through the carefully designed robot behavior. Thus, we can design space-making robots as agents, and their user interactions as "Human Agent Interactions" (HAI) [14]. Since people do perceive agency from space-making robots' behavior, we should carefully design robots' movements as an effective way to enable

HAI interactions between space-making robots and users. This is the "HAI-based Design Paradigm for Space-making Robots."

Sequence	**Research Activity**	**Interactive System**	**The "Lens" Used**
1st	Ethnographic Study	Human-Human	Observation
2nd	Coding of Interaction Patterns	Human-Human	*From the literature:* • Grounded Theory Coding • Partnerships, friendships, companionships, etc. • Joint Action • Living Space, Workplace, etc.
3rd	Coding of Interaction Patterns	Human-"Space-Making Robot"	*Our own:* • Direct Mapping • Conveyed Mapping • Space Agency

Table 1. A design-research framework based on studies, theories, and other literature.

There are many kinds of human-agent interactions that can serve as design inspiration under the HAI-based design paradigm, such as interactions between friends, partners, companions, etc. One way to design space-making robots as our friends, partners, companions, etc. is to follow the "pattern-based, design framework for space-making robots," which is illustrated in Table 1.

This design framework presents a systematic design-research process for understanding human-human interactions, coding these interactions into patterns, and then translating these patterns into the interaction design of space-making robots. Although this framework is validated qualitatively through a design exemplar in

Chapter VI, it is certainly not the only way to implement an "HAI-based design paradigm" rigorously in the design process. The design process, here and more broadly, has always been and will always be diverse, flexible, and creative [15].

In addition, users may prefer space-making robots to be agents in some situations, but only tools in others. Designers should make this design decision case by case based on user preferences and other important factors specific to the nature of the design problems. The author of this dissertation is by no means arguing that space-making robots should only be designed as agents. The author's argument is that space-making robots can be designed as agents when they need to be, and this agency-based design paradigm is solidly based on empirical studies of user perception.

V. FUTURE DIRECTIONS

A. A Validated Scale for "Perceived Agency"

A validated scale of "Perceived Agency" can be a good contribution to robotics and the architecture community. Currently, there are scales measuring children's perceived agency of robotics, which are not applicable to adults [11]. There are also scales measuring people's "Impression of Agent," which relate to whether people perceive a robot as a "good" or "bad" agent [12]. However, there is no validated scale measuring whether or not people perceive robotics as agents. In addition, the seven subconstructs (perceived intelligence, intention, cognition, welcome, collaboration, cooperation, and friendliness) proposed in Chapter V provide very good raw materials for developing a validated scale, since the Cronbach's alpha of these seven subconstructs is 0.91, which is very high [13].

B. A Room Embedded with Multiple Space-Making Robots as a "Space Agent"

In this dissertation, the author proposed and validated that people do perceive agency from the meticulously designed movements of space-making robots. However, in the experiment, the participants attribute the agency characteristics to the space-making robot itself (which is the robotic surface embedded in the wall) instead of to the whole room. Based on this experiment, we can propose the hypothesis that when the whole room is one space-making robot, then people will perceive agency from the whole room. However, this is only a hypothesis waiting for validation. Moreover, in the real settings of smart rooms, it is more likely that multiple space-making robots will be embedded in the room instead of making the whole room one space-making robot. So, the next question the author is really interested in pursuing is this: will people perceive the room embedded with multiple space-making robots and architectural robotics which are coordinated through one AI system to help the users in their daily tasks as an agent? If users do perceive such a room as an agent, then people are actually perceiving agency from an architectural space, which is the concept of "Space Agent." With the validated scale for "Agency Perception" developed, the author will have a more concrete conclusion for this research question.

C. Measuring the "Impression of Agent" for the Smart Room

If a smart room embedded with multiple space-making robots is constructed, the author will test users' "Impression of Agent" using the validated scale [12]. The author is particularly interested in three follow-up questions: 1) Is the user's impression of this room agent shaped by different kinds of interaction modalities?; 2) Is the user's impression of this room agent shaped by the form factors of the space-making robots, robotic furnishings, and the room in general?; 3) Is the user's impression of this room agent contributing to user's short-term and long-term well-being? If it is, how?

D. Investigating Relationships between Users and "Space Agents"

If people do perceive agency from an adaptive and interactive space, and this "space agent" can be designed to be our friends, companions, partners, etc., the relationships between human and their surrounding built environments will be greatly changed. Since "relationship" is the key factor contributing to people's happiness and well-being, it will be very important to investigate how to cultivate a healthy and positive relationship between human users and their agent-like surrounding environments, or "Space Agents."

E. A Grand Vision

All the future works mentioned above are pointing to the same future research direction, which is the "Agency-Based Design Paradigm" not only for "Space-Making Robots," but for adaptive & interactive spaces in general. This design paradigm, if being validated, will greatly shape the future of smart architecture and smart cities. The author is planning to write a book for the "Agency-Based Design Paradigm for Space Agents" in the next few years with more empirical data as support and evidence. Finally, the author would like to conclude this dissertation with a grand vision:

Architecture has always been conceptualized as an environmental system. For the first time in human history, because of AI & Robotics technologies, architecture can be designed, engineered, and evaluated not only as an environment, but an agent that is intelligent, social, emotional, and ethical. What does this mean to our life, our society, and our conceptualization of the world in philosophy?

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[15] H. Osawa and M. Imai, “Morphing agency: Deconstruction of an Agent with Transformative Agential Triggers,” CHI 13 Extended Abstracts on Human Factors in Computing Systems on - CHI EA 13, 2013.

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APPENDIX A

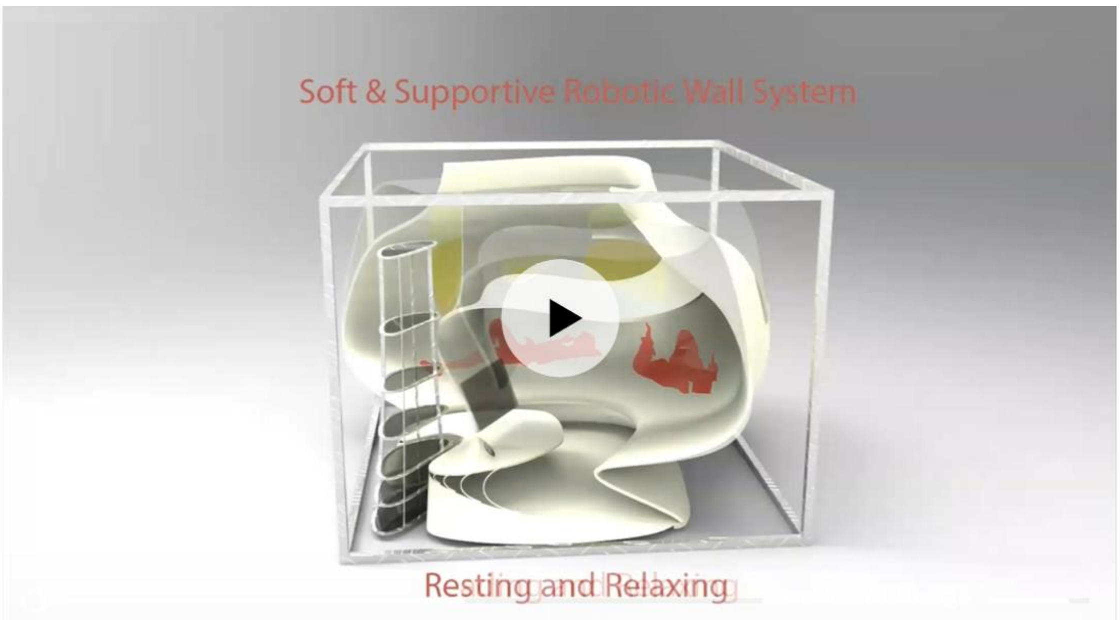
VIDEOS WITH SHORT DESCRIPTIONS

A1. Animation: A Room Alive (Ph.D. Dissertation: Grand Vision).

Video Link:

https://yw6971.wixsite.com/mysite/space-agent-phd-dissertation

Front Page:



Video Description:

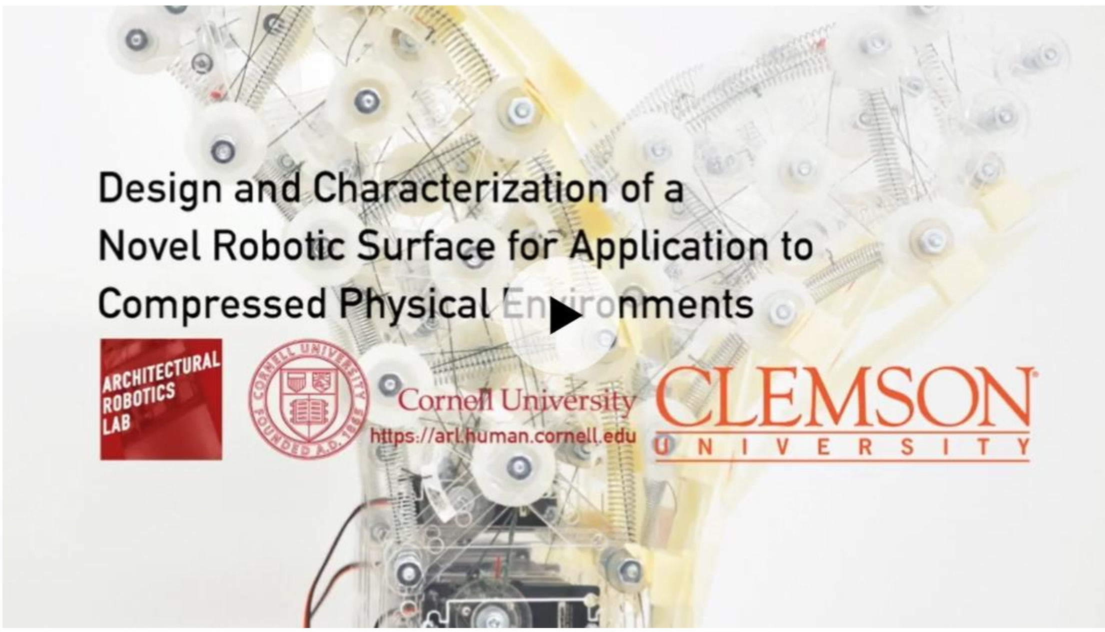
What if one day, your bedroom could reconfigure itself into a living room, an office, a kitchen, a meeting space, a workshop, etc. to support all you need to do within one space? What if you could interact with your surrounding environment as if a partner, a friend, or even an extension of yourself? These ideas may sometimes sound like fantasies; however, current computer and robotic technologies could easily bring at least part of them into reality. In this video, we see the vision that the frontiers of HCI, HRI, and Interaction Design are extending to the spatial.

A2. Video: Design and Characterization of a Novel Robotic Surface for Application to Compressed Physical Environments (ICRA 2019).

Video Link:

https://www.yixiaowang2019.com/pinecone-surface-biomimicry
robotic?pgid=j7ekdg5g-f54ddb58-b05c-4c0d-8145-1cf3ee3eb94a

Front Page:



Video Description:

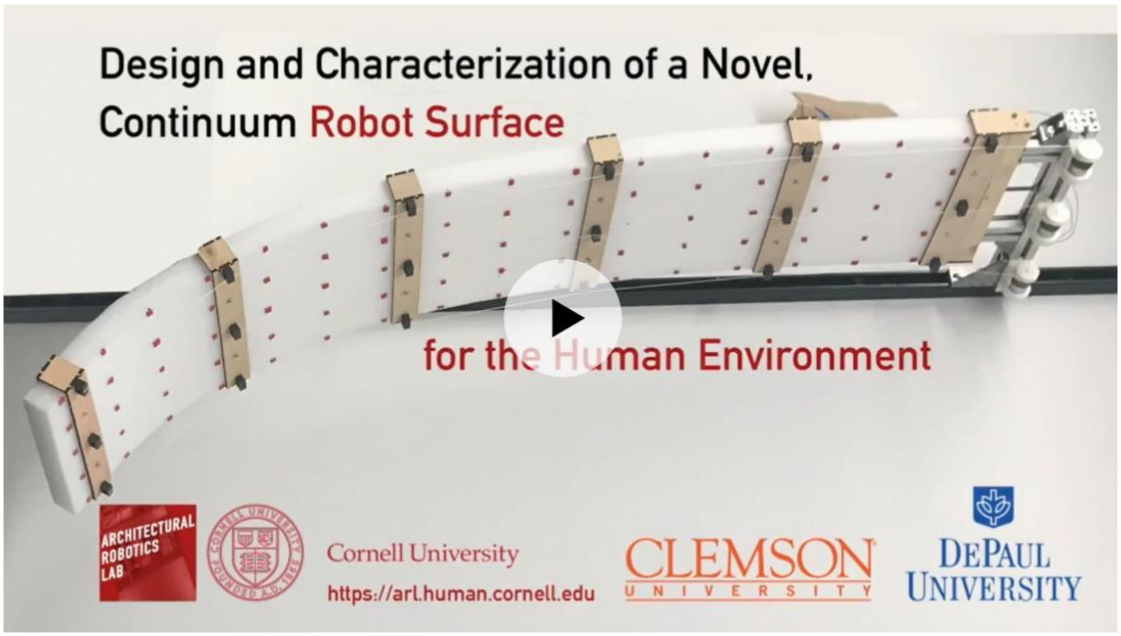
This video presents the whole arc of this continuum robot surface project, including conceptual designs, mechanical mechanisms, prototype dimensions & moving ranges, MATLAB simulations, physical prototype experiments, and potential applications. Four designed configurations: Upright, Forward-bend, Forward-extend, and Angled were presented with simulation and experiment results compared. This continuum robot surface is a design exemplar for continuum robot surface mechanisms with potentials for building scale applications such as fine-tuning a concert hall.

A3. Video: Design and Characterization of a Novel Continuum Robotic Surface (CASE 2019)

Video Link:

https://www.yixiaowang2019.com/space-agent-phd-dissertation?pgid=j7fs81tz-4badd1aa-d596-4fca-9ccc-74e60ee09f0c

Front Page:



Video Description:

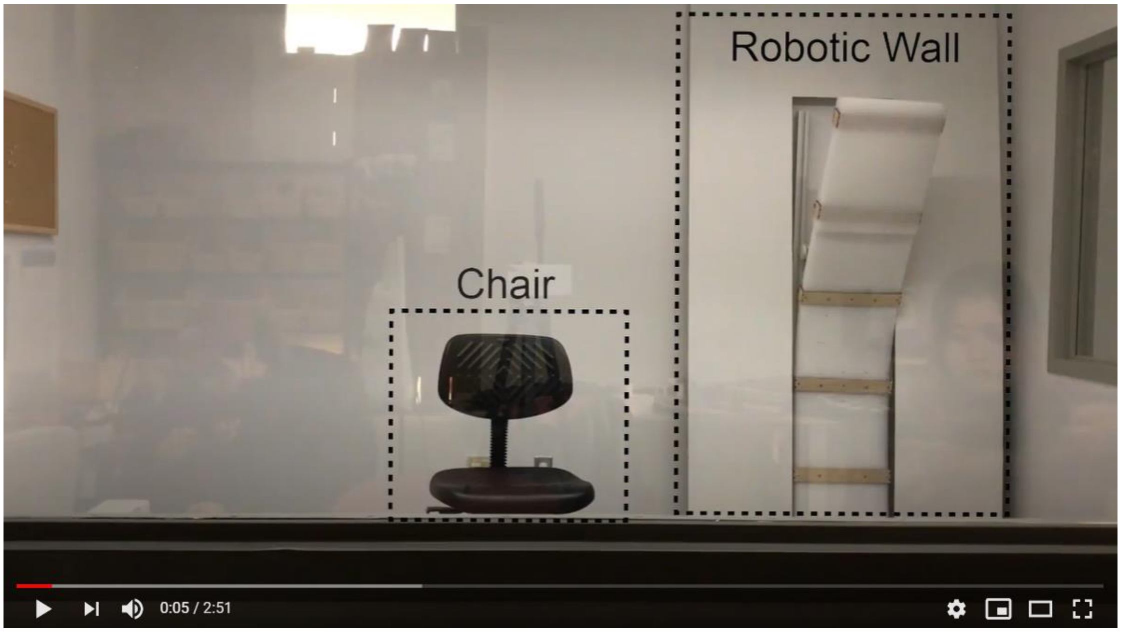
This video presents the whole arc of this continuum foam panel project, including conceptual designs, mechanical mechanisms, prototype dimensions, MATLAB simulations, physical prototype experiments, and potential applications. Five configurations: Rest, Strong-bend, Soft-bend, Twist, and Angled were presented with simulation and experiment results compared. This continuum robot surface is a design exemplar for continuum robot surface mechanisms with potentials for interior scale applications such as autonomous vehicles, space capsules, health facilities, etc.

A4. Video: Treatment Group Participants Co-working with Robot Surface (ROMAN 2020)

Video Link:

https://www.youtube.com/watch?v=gWJ4mJHjfGE

Front Page:



Video Description:

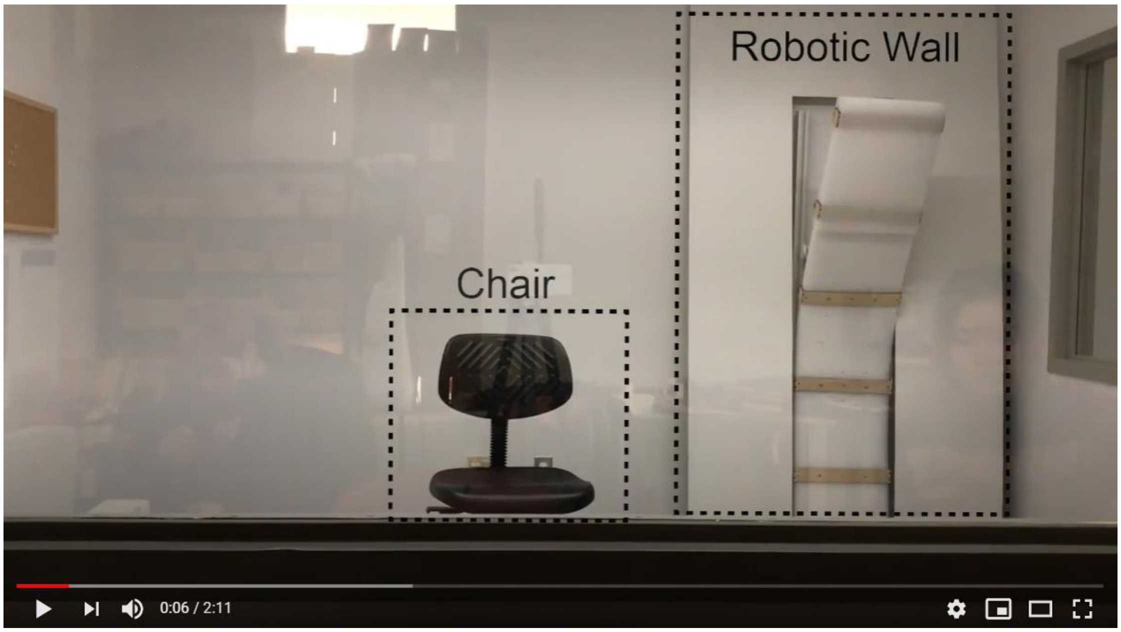
This video describes an in-lab experiment where participants co-work with a continuum robot surface embedded in the wall. Participants were given a piece of thin paper and asked to copy a short paragraph by hand in the experiment room without any desks or tables available. The robot surface will then bend down tentatively to engage the participants for performing this simple task together. Since participants were not told anything about the robot surface behavior or function, many different reactions from the participants were observed and recorded in the experiment process. This video is used in the online experiment for the treatment group.

A5. Video: Control Group Participants Co-working with Robot Surface (ROMAN 2020)

Video Link:

https://www.youtube.com/watch?v=3YHPodF0qRc&t=27s

Front Page:



Video Description:

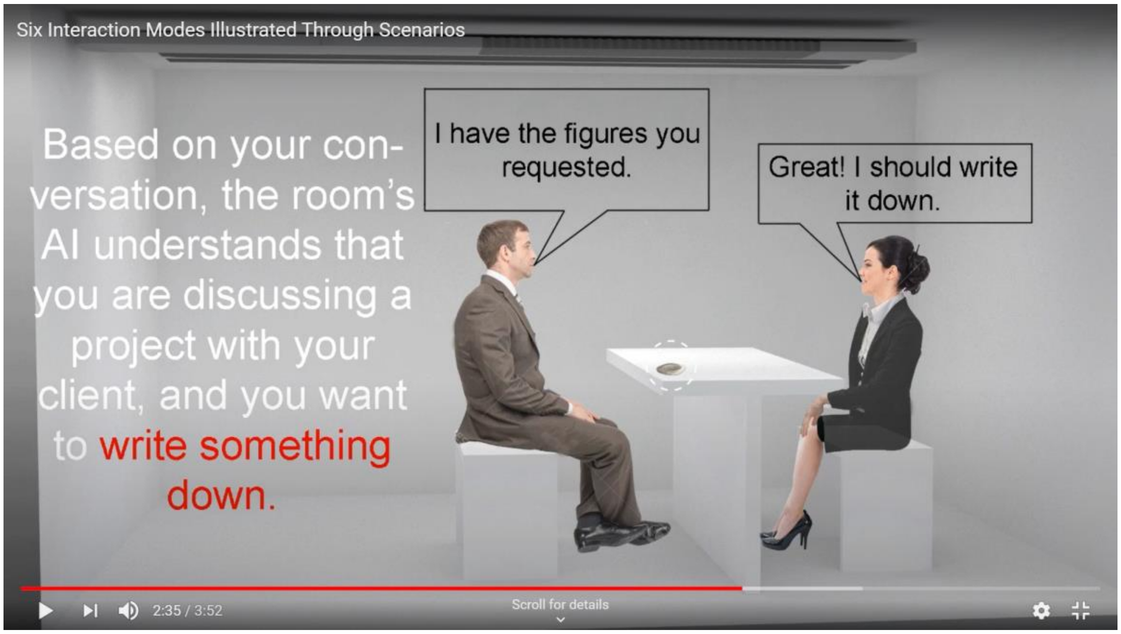
This video describes an in-lab experiment where participants co-work with a continuum robot surface embedded in the wall. Participants were given a piece of thin paper and asked to copy a short paragraph by hand in the experiment room without any desks or tables available. The participants were then given a remote controller from an experimenter, explaining how this robot surface can be controlled. Many different reactions from the participants were observed and recorded when participants performing this simple task. This video is used in the online experiment for the control group.

A6. Video: Six Different Interaction Modes Illustrated Through Scenarios.

Video Link:

https://www.youtube.com/watch?v=ZUMmQMfIHuo

Front Page:



Video Description:

This video describes the six interaction modes designed for the robot surface controls. "Buttons," "Voice Control," "Human Activity Recognition," "Proximity Sensor," and "Graphic User Interface" are proposed and designed by the experimenters, and "Natural Language Processing" is proposed by the participants. Each of five interaction modes proposed by experimenters was illustrated to the participants through a short video like this so that participants understood the basic ideas. The participants then made choices about which interaction modes they prefer most for which tasks or scenarios.

APPENDIX B

QUESTIONNAIRE

Title: How do People Work with Robotic Surface

Description: In this study, you will watch a short video and then answer some questions. Since most of the questions are based on the video, please watch the video carefully, without fast forwarding. This study is completely anonymous and is supposed to be fun and inspiring. Thank you and enjoy!

Q1: What is your gender?

□ Male

□ Female

□ Others

Q2: What age range do you fall into?

□ 18 to 24

□ 25 to 39

□ 40 to 60

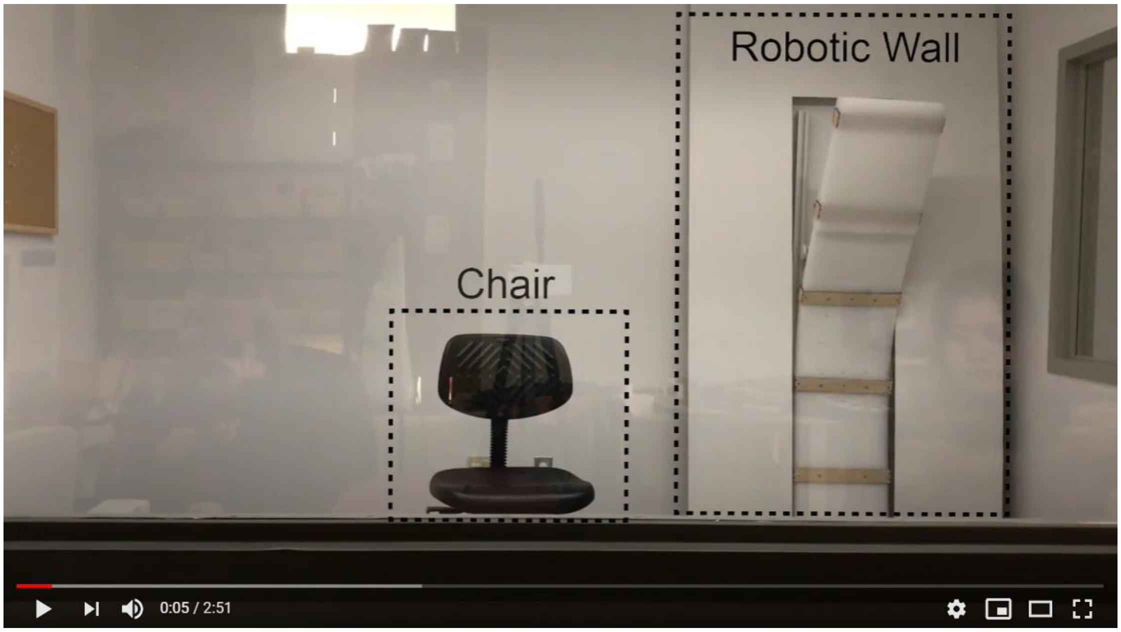
□ 60 plus

Q3: On average over the past year, how many hours did you spend each day on a computer and smart phone combined? (Please type in a number only)

____

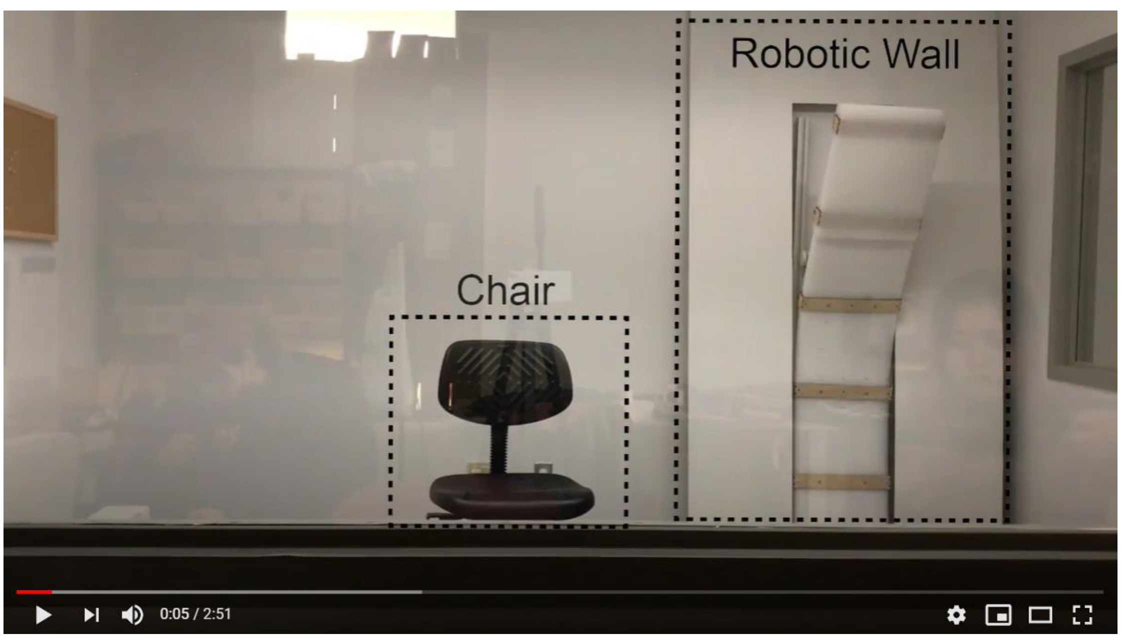
End of Block 1

Here is the video for you to play (Appendix A4 for Treatment Group, and A5 for Control Group). After the timer counts down to "0," you can proceed to the questions.



End of Block 2

Below are questions about the video you just viewed (Appendix A4 for Treatment Group, and A5 for Control Group). You can review the video, shown below, if it helps you answer any questions.



Q4 *(Treatment Group)*: Imagine you participated in this in-lab experiment, how would you react?

□ I would use the robotic surface as the writing surface.

□ I would notice the robotic surface and its movement, but still prefer to use something else as a writing surface.

□ I would ignore the robotic surface and its movement.

□ Others

Q4 *(Control Group)*: Imagine you participated in this in-lab experiment, how would you react?

□ I would use the robotic surface as the writing surface.

□ I would not use the remote controller at all.

□ I would play with the remote controller at first, and then use something else as a writing surface instead of the robotic surface.

□ Others

Q5: Briefly explain the reason for your reaction you selected above. (If you selected "Others," please specify how you would react, and then briefly explain the reason for your reaction.)

____

Imagine, once again, that you participated in this experiment, and answer the following questions:

Q6: The robotic surface seemed to do something for you.

Strongly Disagree	Disagree	Somewhat disagree	Neutral	Somewhat agree	Agree	Strongly agree
○	○	○	○	○	○	○

Q7: The robotic surface seemed to think when it was doing something for you.

Strongly Disagree	Disagree	Somewhat disagree	Neutral	Somewhat agree	Agree	Strongly agree
○	○	○	○	○	○	○

Q8: The robotic surface was moving automatically.

Strongly Disagree	Disagree	Somewhat disagree	Neutral	Somewhat agree	Agree	Strongly agree
○	○	○	○	○	○	○

Q9: The robotic surface seemed to recognize that you needed a hard surface to write on.

Strongly Disagree	Disagree	Somewhat disagree	Neutral	Somewhat agree	Agree	Strongly agree
○	○	○	○	○	○	○

Q10: The robotic surface didn't intend to do anything for you.

Strongly Disagree	Disagree	Somewhat disagree	Neutral	Somewhat agree	Agree	Strongly agree
○	○	○	○	○	○	○

Q11: The robotic surface had no intelligence at all.

Strongly Disagree	Disagree	Somewhat disagree	Neutral	Somewhat agree	Agree	Strongly agree
○	○	○	○	○	○	○

Q12: The robotic surface seemed to understand your needs.

Strongly Disagree	Disagree	Somewhat disagree	Neutral	Somewhat agree	Agree	Strongly agree
○	○	○	○	○	○	○

Q13: The robotic surface was acting deliberately.

Strongly Disagree	Disagree	Somewhat disagree	Neutral	Somewhat agree	Agree	Strongly agree
○	○	○	○	○	○	○

Q14: The robotic surface was trying to provide a work surface for you to write on.

Strongly Disagree	Disagree	Somewhat disagree	Neutral	Somewhat agree	Agree	Strongly agree
○	○	○	○	○	○	○

Q15: The robotic surface was interacting with you.

Strongly Disagree	Disagree	Somewhat disagree	Neutral	Somewhat agree	Agree	Strongly agree
○	○	○	○	○	○	○

Q16: The robotic surface was trying to be cooperative.

Strongly Disagree	Disagree	Somewhat disagree	Neutral	Somewhat agree	Agree	Strongly agree
○	○	○	○	○	○	○

Q17: The robotic surface was completely controlled by you.

Strongly Disagree	Disagree	Somewhat disagree	Neutral	Somewhat agree	Agree	Strongly agree
○	○	○	○	○	○	○

Q18: The robotic surface was trying to be friendly.

Strongly Disagree	Disagree	Somewhat disagree	Neutral	Somewhat agree	Agree	Strongly agree
○	○	○	○	○	○	○

Q19: The robotic surface didn’t recognize what you needed to do.

Strongly Disagree	Disagree	Somewhat disagree	Neutral	Somewhat agree	Agree	Strongly agree
○	○	○	○	○	○	○

Q20: The robotic surface was ignoring your intentions.

Strongly Disagree	Disagree	Somewhat disagree	Neutral	Somewhat agree	Agree	Strongly agree
○	○	○	○	○	○	○

Q21: The robotic surface was trying to be welcoming.

Strongly Disagree	Disagree	Somewhat disagree	Neutral	Somewhat agree	Agree	Strongly agree
○	○	○	○	○	○	○

Q22: The robotic surface was collaborating with you.

Strongly Disagree	Disagree	Somewhat disagree	Neutral	Somewhat agree	Agree	Strongly agree
○	○	○	○	○	○	○

Q23: How do you feel about the robotic surface in general?

Strongly Disagree	Disagree	Somewhat disagree	Neutral	Somewhat agree	Agree	Strongly agree
○	○	○	○	○	○	○

Q24 *(Treatment Group Only)*: What did you think was happening when you saw the robotic surface move? Please type your answer in the box below:

Q25 *(Treatment Group Only)*: Assuming the robotic surface functioned properly, how did you interpret the robotic surface's movement? Please type your answer in the box below:

Q25 *(Treatment Group Only)*: Do you consider the robotic surface to be a partially intelligent agent with at least some level of intelligence? Why? Please type your answer in the box below:

APPENDIX C

CODE

(Contribution of Richa Sirohi and Chase Frazelle)

C1. RGB Sampling Code for Continuum Foam Panel (CASE 2019)

```
colorDevice = imaq.VideoDevice('kinect',1,'BGR_1920x1080');
depthDevice = imaq.VideoDevice('kinect',2,'Depth_512x424');

step(colorDevice);
step(depthDevice);

colorImage = step(colorDevice);
depthImage = step(depthDevice);

imshow(colorImage);

disp('Releasing Kinect')
release(colorDevice);
release(depthDevice);
delete(colorDevice);
delete(depthDevice);
```

C2. 3-Dimentional Plot Output for Continuum Foam Panel (CASE 2019)

```
clear
clc
close all

maxNumReg = 255; %maximum number of detectable regions, recommended to set
                 %well above expected value of regions
minRegSize=1; %minimum size for a region to be detected (in pixels)
rMin=97; %min and max RGB values for desired region
rMax=185; %a more robust solution would be to check ratio between
gMin=29; %RGB channels
gMax=185;
bMin=25;
bMax=185;

fcn = 0; %Set fcn=0 for recording and processing
    %Set fcn=1 for just recording data
    %Set fcn=2 for processing pre-recorded data

if(fcn==0 || fcn==1) %connects and starts the camera
  colorDevice = imaq.VideoDevice('kinect',1,'BGR_1920x1080');
  depthDevice = imaq.VideoDevice('kinect',2,'Depth_512x424');

  step(colorDevice); %inits device
  step(depthDevice);

  colorImage = step(colorDevice); %capture color and depth image
  depthImage = step(depthDevice);

  COLS=640;
```

```
    ROWS=480;
end

try

    if(fcn==0 || fcn==1) %create point cloud
        ptCloud = pcfromkinect(depthDevice,depthImage,colorImage);
        ptCloud = removeInvalidPoints(ptCloud); %%Optional, but will need
                                          %to export and reimport
                                          %ptCloud
        if(fcn == 1)
            pcwrite(ptCloud,'OctArmView.ply'); %I suggest changing file
                                          %name to automatically
                                          %include time will produce a
                                          %more unique filename
            error('Skip to end of file'); %nothing else needs to be done
                                     %but to disconnect camera
        end
    elseif(fcn==2)%read in point cloud
        ptCloud = pcread('OctArmView.ply');
    end

    cImage = ptCloud.Color;
     figure
     imshow(colorImage) %%for debugging to verify camera works and sees
     %objects

    location = ptCloud.Location; %ptCloud.Location is read only,
                              %manipulate externally
```

```
 %for when cImage is in vector format, with unknown dimensions
mask = ((cImage(:,1)>=rMin) & (cImage(:,1)<=rMax) & ...
        (cImage(:,2)>=gMin) & (cImage(:,2)<=gMax) & ...
        (cImage(:,3)>=bMin) & (cImage(:,3)<=bMax));



%mask out unneeded RGB pixels
maskedRgbImage = bsxfun(@times, cImage, cast(mask, 'like', cImage));
maskedLoc1 = bsxfun(@times,location(:,1),cast(mask,'like',location(:,1)));
maskedLoc2 = bsxfun(@times,location(:,2),cast(mask,'like',location(:,2)));
maskedLoc3 = bsxfun(@times,location(:,3),cast(mask,'like',location(:,3)));



player = pcplayer(ptCloud.XLimits,ptCloud.YLimits,ptCloud.ZLimits,...
    'VerticalAxis','y','VerticalAxisDir','down');

ptCloud.Color=maskedRgbImage; %reassign extracted color values

view(player,ptCloud); %view identified pixels, should be only colored pixels

xlabel(player.Axes,'X (m)');
ylabel(player.Axes,'Y (m)');
zlabel(player.Axes,'Z (m)');

%extract points of interest from all points
extracted=[maskedLoc1(mask) maskedLoc2(mask) maskedLoc3(mask)];
labels=zeros(length(extracted),1);

TotalRegions=0;
```

```
Region=zeros(maxNumReg,3); %preallocate maximum number of regions

for r=1:length(extracted)

  if labels(r) ~= 0
     continue;
   end

   sum=0;
   for r2=-2:2
      if(r+r2>=1 && r+r2 <=length(extracted))
         sum=sum+labels(r+r2);
      end
   end

   if sum == 0        % condition for seeding a new region is zero sum

    fprintf('New region at x= %f y=%f z=%f\n',
num2str(extracted(r,1)),num2str(extracted(r,2)) ,num2str(extracted(r,3)));
      TotalRegions=TotalRegions+1;
      if (TotalRegions == maxNumReg)
         disp('Segmentation incomplete.  Ran out of labels.');
         break;
      end

      [labels, RegionSize,indices,center] =
RegionGrowBrute(extracted,labels,r,nan,TotalRegions);
      if (RegionSize < 1)
      erase region (relabel pixels back to 0)
         for i=1:RegionSize
```

```
                labels(indices(i))=0;
              end
              TotalRegions=TotalRegions-1;

          else
              fprintf('Region labeled %d is %d pixels in size\n',TotalRegions,RegionSize);
              Region(TotalRegions,:)=center(:);
          end
      end
   end



   fprintf('%d total regions were found\n',TotalRegions);
   for g=1:TotalRegions
      fprintf('Region %d at
(x,y,z)=(%f,%f,%f)\n',g,Region(g,1),Region(g,2),Region(g,3));
   end

   figure
   hold on
   scatter3(extracted(:,1),extracted(:,2),extracted(:,3),1,'o');
   %scatter3(Region(1:TotalRegions,1),Region(1:TotalRegions,2),Region(1:TotalRegi
ons,3),100,'*r');
   axis equal
%     maskedDepthMat=reshape(,480,640);

catch ME %catches exceptions so that camera can be disconnected properly
    disp('Exception thrown!\n');
   disp(ME)
   disp('hello world')
```

```
end

%%Must run, even if file fails
if(fcn==0 || fcn==1)
    disp('Releasing Kinect')
    release(colorDevice);
    release(depthDevice);
    delete(colorDevice);
    delete(depthDevice);
end
```

technical drawings

code (Richa and Chase)

A3. Sub-function (RegionGrowBrute) for Continuum Foam Panel (CASE 2019)

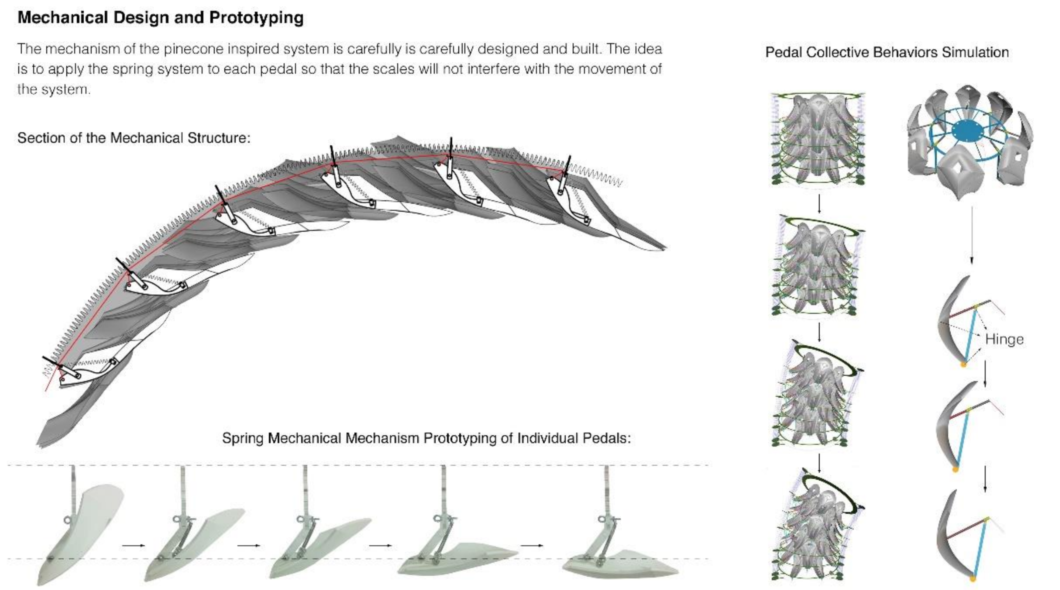
```
function [labels,count,indices,center] = RegionGrowBrute(points,... %set of x,y,z coords, arranged as image
            labels, ... %
            r,c, ...        /* pixel to paint from */
            new_label)          %/* output:  count of pixels painted */

%%Start of function
  newPixel=zeros(3,1);

  count=0;

  indices=zeros(length(points),1);
  labels(r)=new_label;

  centerX=points(r,1);
  centerY=points(r,2);
  avgDepth=points(r,3);

  count=1;
  indices(count)=r;

  for i=1:length(points)

    if labels(i)~=0
      continue;
    end
    if i==r
      continue;
    end
```

```
%      test criteria to join region */

        if (abs(centerX-points(i,1))>0.02 || abs(centerY-points(i,2))>0.02 || abs(avgDepth-
points(i,3))>0.01)
            continue
        end

        labels(i)=new_label;

        count=count+1;

        if (exist('indices','var'))
            indices(count)=i;
        end

        newPixel(1)=points(i,1);
        newPixel(2)=points(i,2);
        newPixel(3)=points(i,3);

        centerX=(centerX*(count-1)+newPixel(1))/count;
        centerY=(centerY*(count-1)+newPixel(2))/count;
        avgDepth=(avgDepth*(count-1)+newPixel(3))/count;

    end
%   fprintf("New Avg: %.3lf %.3lf %.3lf\n",avgNorm[0],avgNorm[1],avgNorm[2]);
    center=[centerX,centerY,avgDepth];
end
```

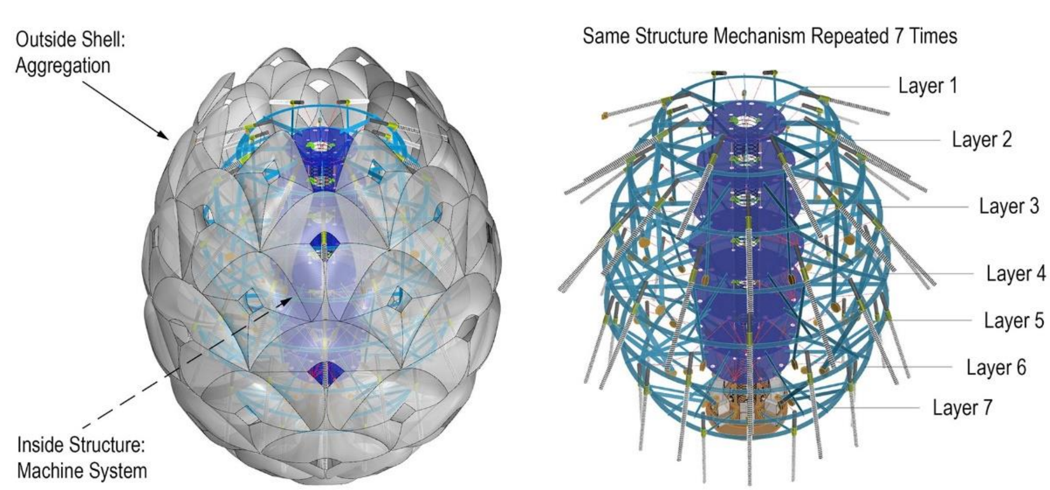
APPENDIX D

D. DRAWINGS

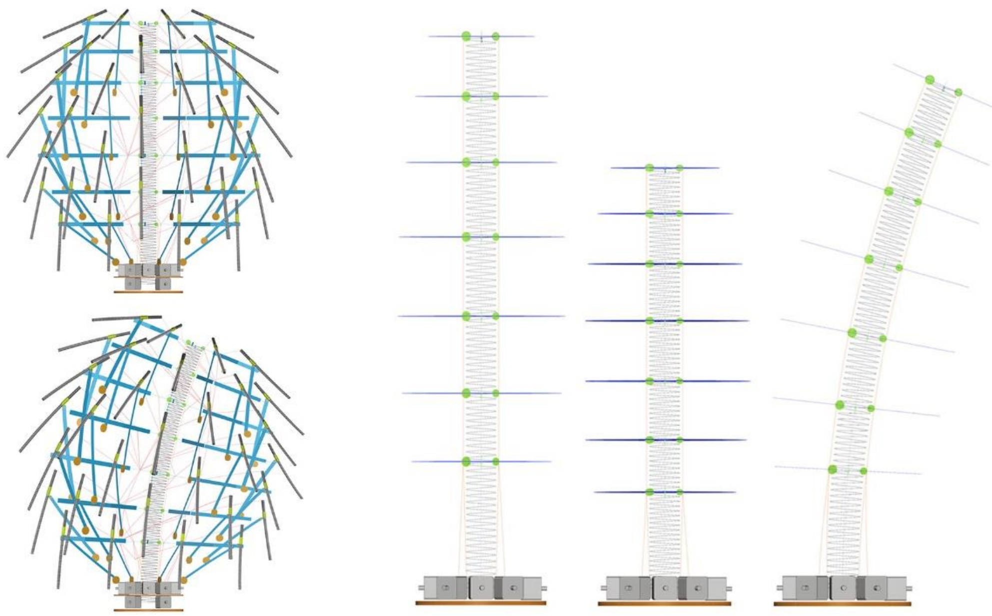
D1. Pinecone-inspired Conceptual Drawings for the Continuum Robot Surface



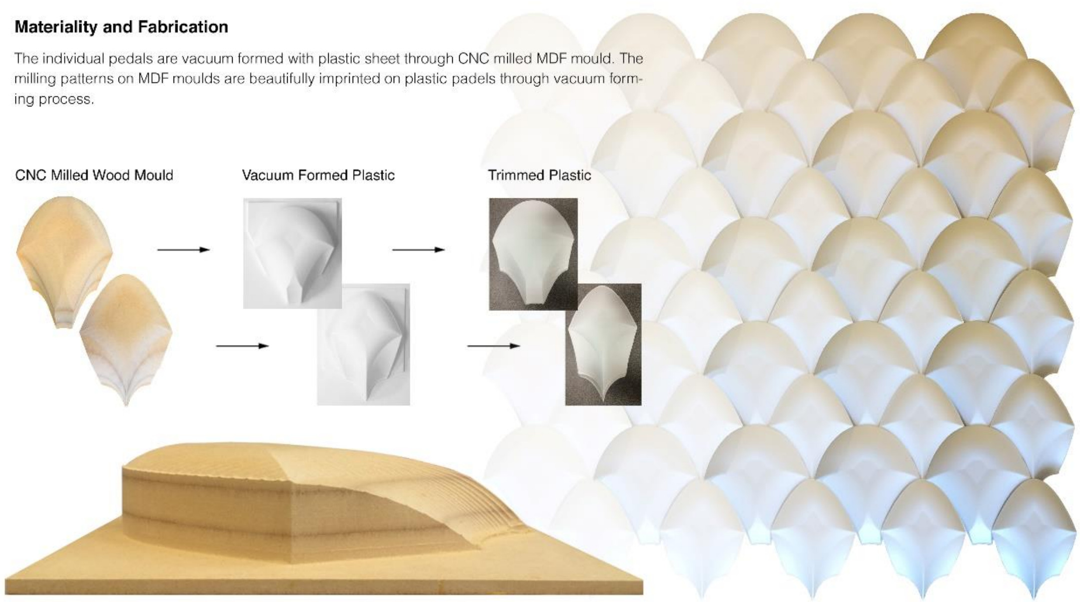
D1-1. Mechanical Design and Prototyping



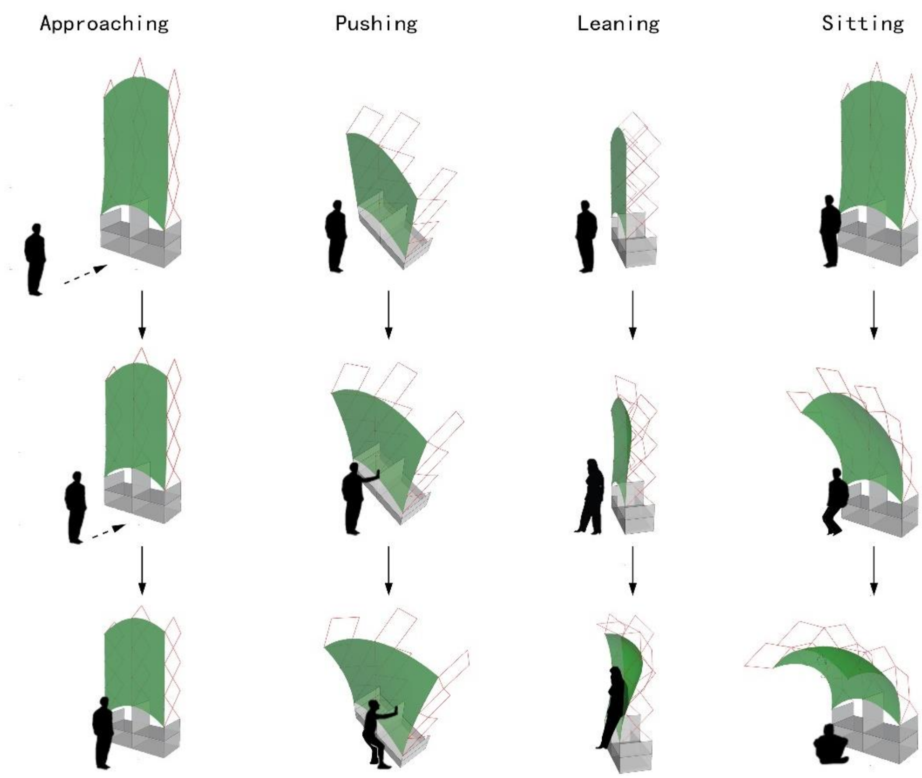
D1-2. An Artificial Pinecone with Tendon Driven Actuation System



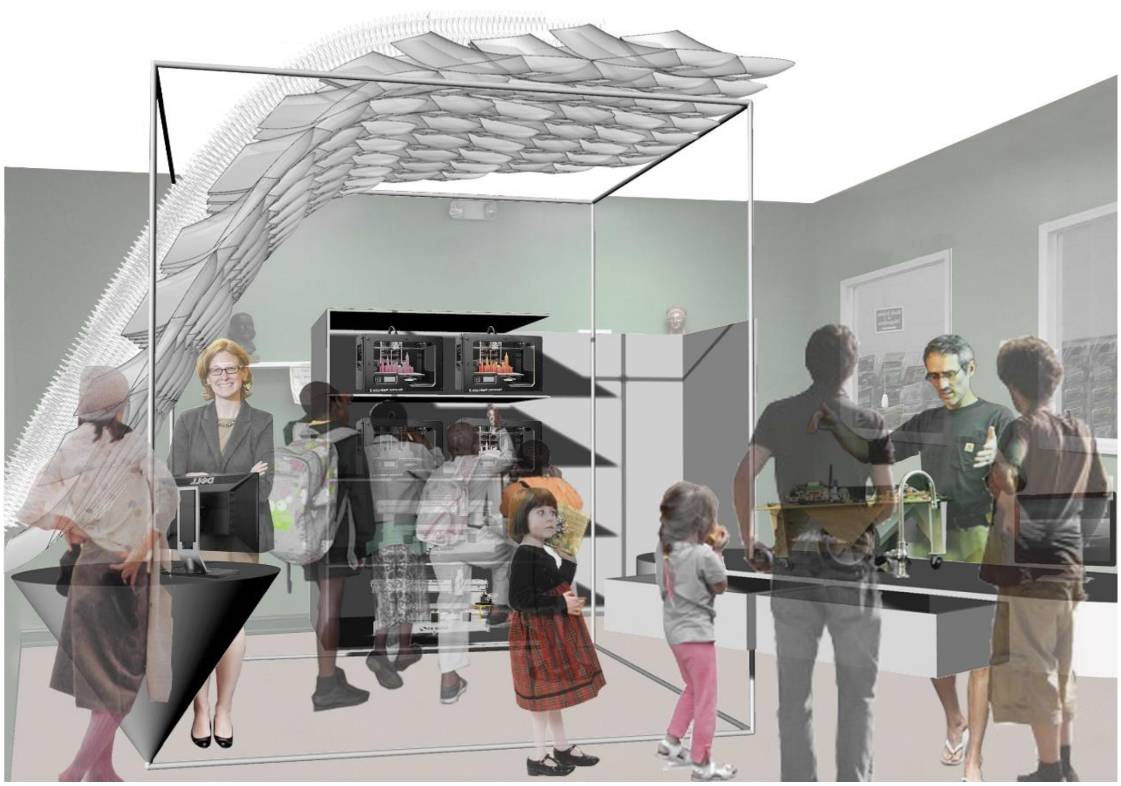
D1-3. The Bending Mechanism of “Pinecone”



D1-4. Materiality and Fabrication

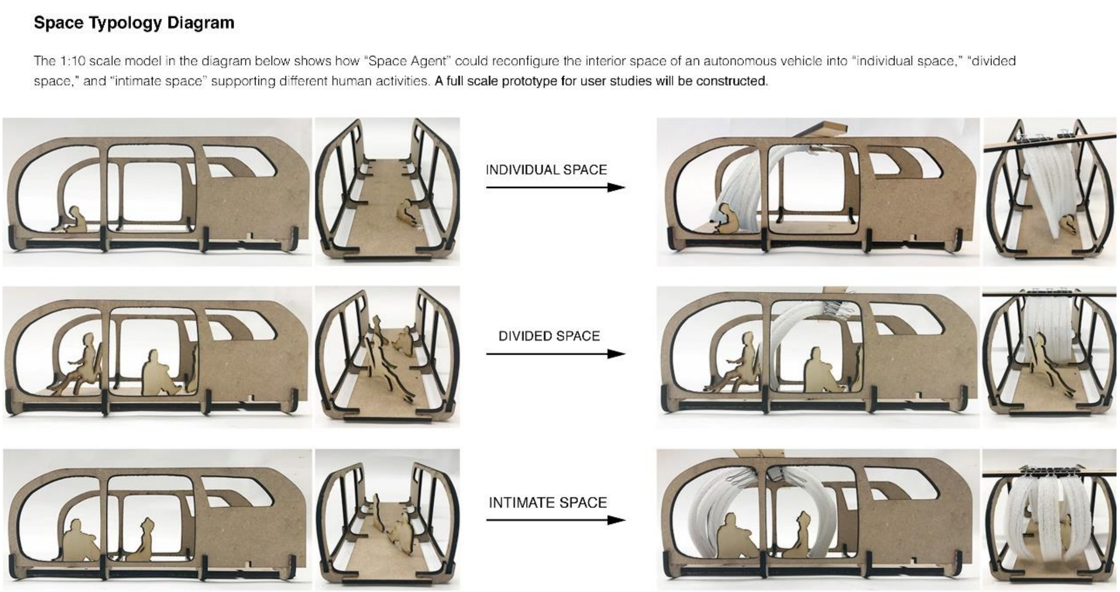


D1-5. Human-Surface Interaction Diagram

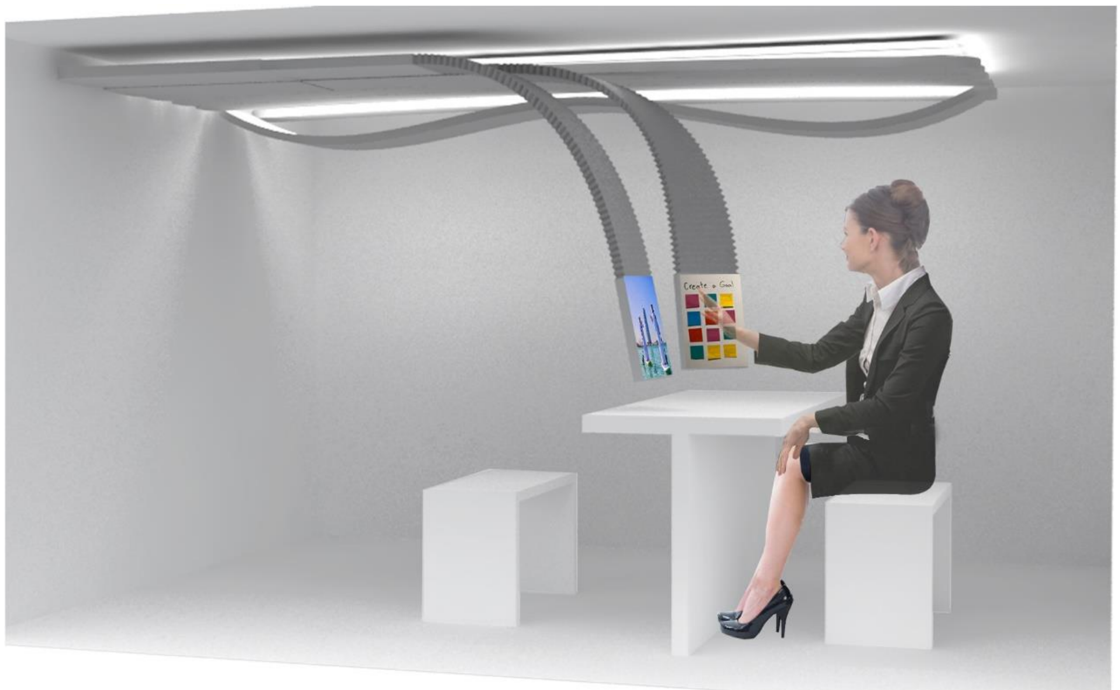


D1-6. Applications: Transforming Library Space

D2. Robotic Foam Panel Conceptual Drawings



D2-1. Space Typology Diagram



D2-2. Robotic Foam Panel Offering Tablets (Application 1)

D2-3. Robotic Foam Panel Diffusing Lights (Application 2)

D2-4. Robotic Foam Panel Changing Atmosphere (Application 3)

D2-5. Robotic Foam Panel for Presentation (Application 4)