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Design of Two Morphing Robot Surfaces and Results from a User Study On What People Want and Expect of Them, Towards a "Robot-Room"

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Abstract— **We propose, examine prototypes of, and collect user input on morphing robotic surfaces, "robot-room" elements that, individually or in combination, change the functionality of the rooms we live in, directly controlled by the room's occupants engaging with it. Robot-rooms represent an advance in human-robot interaction whereby human interaction is within a machine that physically envelops us. We discuss the motivation for such robot-rooms, present initial work aimed at their physical realization, and report on a user study of 80 participants to learn what people might want of and expect from robot rooms, the results of which will inform both the iterative design of the robot room and the thinking of our community as it grapples with how we want to live with (and "in") robots.**

Keywords: **Robot surfaces, User studies**

I. Introduction

While the robotics research community learns more about how people receive, perceive, and interact with robots in their everyday lives, these robots are commonly robot arms, mobile robots, or humanoid or otherwise animal-like forms. Robot-rooms are a new category of robots: distinct for not being a compact or linear body like the robots just listed and for not existing within a space as do the robots just listed. Robot-rooms are rather a space-making body that represent a new kind of human-machine interaction whereby people are enveloped by the robot (Fig. 1). As such, Robot rooms offer researchers both a unique set of technical challenges and and design interaction challenges in understanding of how people – dwellers in tight confines – live with and in robots. As we increasingly expect robots to become a part of our everyday lives, developing a robot-room represents a transformative advance in human-centered robotics.

In the thinking of Gordan Pask [12] in the 1960s, Negroponte [11] in the 70s, and Mitchell [10] in the 80s-90s, we can find semblances of a robot-room. However, the "intelligent environments" of Pask [12] and since, many under the IEEE conference of the same name, are more focused on sensing and data acquisition or discrete robotic artifacts, not on the physical reconfiguration of room space. Likewise, the "soft architecture machine" [11] and "the responsive houses" [1] of Negroponte and peers were significant but early efforts at robot-rooms, but none of these were developed as fully functioning, full scale prototypes evaluated for how they serve the needs of inhabitants. In e-topia [10], Mitchell envisioned a "robot for living in," a revolutionary concept for rooms and buildings, but again not yet manifested as a habitable room. Physical manifestations of the responsive house following this largely theoretical trajectory include :Robotic-Micro Rooms[19], the Meta-Room[18], the Smart Room, and Aware House[13]; but again, these rooms are focused more on approaches to sensing in space, not on the cyber-physical reconfigurability of rooms. In this sense the physical spaces become smarter, but the way the human occupants of the spaces use and interact with their environments remains essentially the same as in traditional spaces.

In this work, we alternatively explore the idea of endowing human-centered, physical spaces at the scale of a room with "embodied intelligence" via the ability to modify key parts of their shape, operating interactively with, and for, the humans who share the space. A demonstration of a "morphing" living space is the "Hong Kong Space Saver," a 330 sq.ft. apartment designed by architect Gary Chang [2]. The owner, Chang himself, manually configured sliding walls within the unit to create, in a single room, any one of twenty-four different living configurations. But while Chang's home is compelling and informative, it is not robotic, not interactive nor intelligent. Closer to our vision is TU Delft's MuscleBody [7], a bulbous, pneumatically-actuated space that accommodates several inhabitants who, by their actions, cause shape transformations, without, however, the ability to directly control it.

We propose, examine prototypes of, and collect user input on morphing robotic surfaces, robot-room elements that, individually or in combination, change the functionality of the room, directly controlled by the room's occupants engaging with it. It is in this sense we envision a shape morphing interactive "robot-room." Shape morphing is formally the process of transitioning between 3D shapes driven by the design and/or structure of the system and the materials used in the said system [17]. The prototypes described in this paper are a specific example of this technique. Specifically, we focus on shape morphing between pairs of specific shapes, achieved by locally tailoring the response of a flexible surface to a suitable external stimulus.

While morphing robotic surfaces is a relatively new idea, there have been a number of preliminary studies. Initial work from some of the authors of this paper in [9] reported on the development of a morphable foam surface actuated by embedded pneumatic muscles, and modeled its forward kinematics. The approach was extended to develop a lumped

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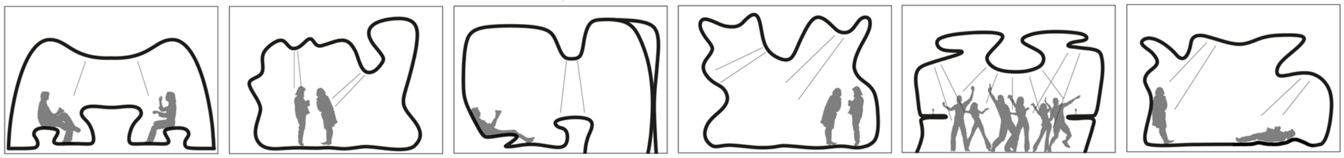

Fig. 1. In concept, a room that physically transforms into other places, for practical ends (dining/office) or "elsewhere.".

mass dynamic model in [6]. An alternative approach to the design of robotic surfaces, inspired by pellicular structures in nature, is presented by others outside our group [4]. Surface actuation via embedded, remotely actuate tendons is explored, again from our group in [15]. More recently, we reported on our design and demonstration of robot surfaces based on braided pneumatic muscles [16].

The two specific robot surface designs and their initial prototypes presented in the next section, Section II, differ from and add to this literature, in that instead of the actuation being via surface-integrated continuum elements, the actuation is achieved by rigid elements interacting (in the interior and at the boundary, respectively) of flexible surface material. In Section III, we turn attention to the human dimension of this research, reporting on a study conducted with human subjects that help our research team frame next steps in the application of the novel elements, in multiples distributed in a room, to form an interactive robot-room supporting human needs and wants of a robot at the scale of the environment.

II. Realization of Robot-Rooms

A. Vision and Physical Prototypes

In our previously published vision statement [5], we defined a robot-room as an "articulated, programmable, physical environment embedded with integrated digital technologies." From the same prior publication, "the novel aspect of a robot-room is its ability to continuously 'morph' to accommodate a wide range of user need by way of its smooth, continuously deformable surfaces." We envisioned these surfaces being, for example, "a storage wall that bends to become a ceiling that finally becomes four moving arms holding computer screens, and a morphing work surface." Also in the same paper, we categorized three behaviors of a robot surface: bending, twisting, and shape shifting. We define two concepts for a robot-room, drawn again from our earlier "vision" paper [5]: "Concept-1," defined as "a typical room with…an insertion of a series of shape-shifting, ribbon-like components"; and "Concept-2," defined as "a seamless, three dimensional envelope rather than the collection of components." In Fig. 2, we illustrate these two concepts in diagrammatic terms: the Components-in-a-room concept ("A"); and the Whole-room concept ("B"), made of three modules: a plane (d), a corner (e) and an angle (f) that together, in multiples, create a seamless room envelope. Fig. 2 also offers visualizations (from our earlier work) of the two concepts: "C" being suggestive of the Components concept; and "D" being suggestive of the Whole-room concept. We are currently constructing and testing the modules in "A" and "B".

B. Prototype 1

"Prototype 1" is a version of the Components-in-a-room concept ("A"), specifically, component (b) which is the floor component in a robot room concept. The prototype is a multi-functional chair/Chaise lounge that is designed to transform itself into either a bed or a table based on user need.

Fig. 3 (A) represents the side view of prototype 1 in it's "Chaise lounge/chair" configuration, Fig. 3 (B) represents the same in it's bed/table configuration. The basic design philosophy was to use surface on surface interaction to create the desired change in shape. This change in shape was achieved by the interaction between a set of three rigid 3D printed flaps (Fig. 3 (A) and (B)) which are actuated from $0°$(natural chair/Chaise lounge configuration) to $90°$(bed/table configuration) sliding across the interior of a piece of foam which forms the surface of prototype 1. Each flap measures approximately 11.85x9x0.2inches and is actuated using a pair of MG995 servo motors.The current configuration (angle) is displayed on an LCD screen. At the heart of the system is an Arduino UNO, which is used to drive and control the motors and all the electronics used in the prototype. The flaps were designed using Solid works and 3D printed using an Ultimaker S5.

C. Prototype 2

"Prototype 2" is a version of the Components-in-a-room concept (Fig. 2. "A") and was specifically made to emulate the hypothesized designs in Fig. 2. The prototype is a multi-functional surface that could fold into a wall that is designed to transform itself into either a seat, booth, or divider based on user need.

Fig. 4 shows the prototype evolving through two stages of its configuration change. The change in shape is accomplished through controlling the configuration of two parallel linkages, affixed to the boundary of a flexible surface. A dual rack and pinion system controls each boundary linkage, with each end of the linkage attached to one of the racks. One rack moves vertically while the other moves horizontally. The combination of these movements allow for the linkages to reach a variety of configurations, in turn shaping the 2D surface connected between them. The pinions are integrated with 360^o servo motors which directly control their movements. An Arduino runs the code that moves the system between elected configurations. The linkages of the system support a foam or like surface forming a continuous spline akin to what is shown in prototype A.

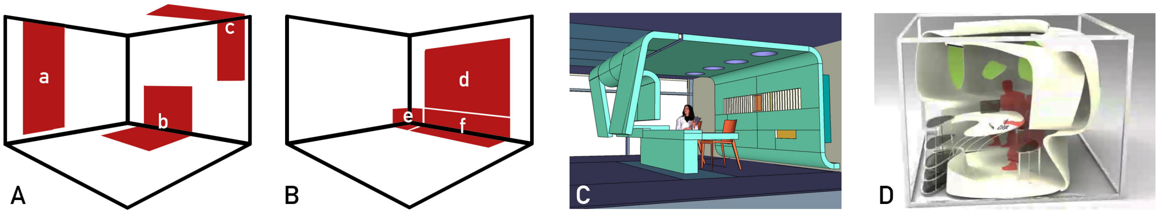

Fig. 2. Two robot-room concepts and semblances of what they might look like: (A) the Components-in-a-room concept where (a), (b) and (c) represent three robot-surface components; (B) the Whole-room concept, made of three modules: a plane (d), a corner (e) and an angle (f) that together, in numbers, make a room envelope; (C) and (D) are visualizations we made some years ago that, respectively, are suggestive of the Components and Whole-room concepts.

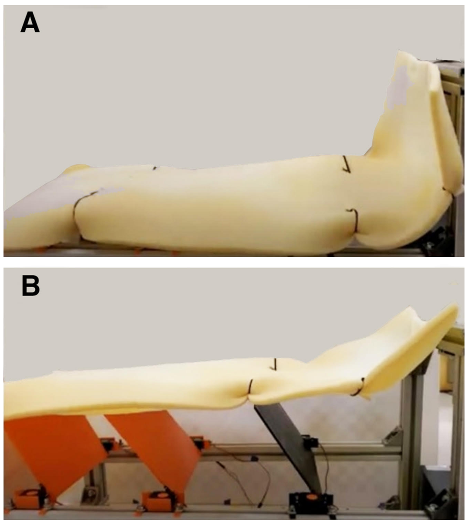

Fig. 3. Side view of prototype A and it's two configurations: (A) a chaise lounge for relaxing, and (B) a bed for sleep or rest.

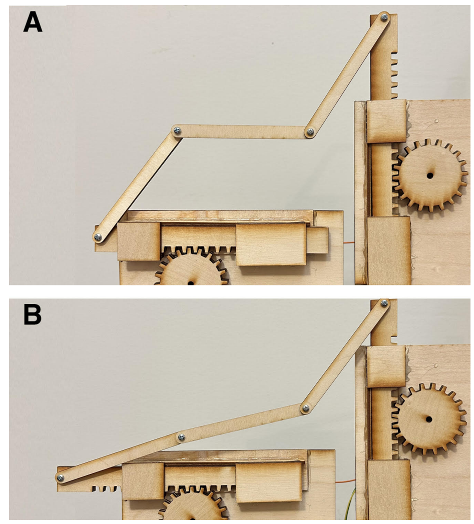

Fig. 4. Prototype B and two of its many configurations: (A) a chaise lounge or comfortable chair for, e.g., TV watching, and (B) a reclining bed for, e.g., reading.

III. Motivating Use Cases for a Robot-Room

We envision the designs and prototypes introduced in the previous section to be distributed in some numbers in a room, at floor level, below the ceiling, and perhaps in between and within the space of the room to form a robot room as suggested in Fig. 2. We chose the home as the site for a robot room given that the home however manifested—house, apartment, co-op, co-housing—is the building typology that accommodates the widest range of human activity: a place for rest, meal preparation, sleeping and socializing, also an office, a school, a playground and a gym. On Earth, as we mass-urbanize, as land in certain regions becomes more prohibitively scarce and expensive, and as we spend more time doing more things at home, our homes, getting smaller, necessitate more physical affordances tuned to our busy lifestyles, on the go, at home. Complicating the strain on the over-programmed home are two associated trends: mass-urbanization and the shrinking size of urban dwellings. By 2050, two-thirds of the Earth's population is expected to reside in urban areas [14]. Meanwhile, the most populated cities are experiencing unprecedented population growth. To accommodate the growing number of urban dwellers, homes are getting smaller: in New York City, dwellings now average 414 sq. ft. per person, in Paris, 388 sq. ft., and in Hong Kong (where home prices have tripled in a decade) 160 sq. ft. and, for subdivided apartments, a mere 48 sq. ft. [14]. The main room of a small home is an ideal site for a robot-room that can actively reconfigure itself to make many places – practical and escapist.

We pose two, core research questions: (1) how can a home be outfitted with a robot-room that re- configures into "many places", practical and escapist – serving effectively as an "everywhere home"? and (2) how are inhabitants of a robot-room supported and augmented by it, following real-world needs? To responsibly respond to these research questions, we identified real-world needs for a robot-room by turning to how people living today reported on their problems and opportunities of living in small, relatively confined living spaces as documented in two articles from The New York Times appearing in the period during which many of us were under a quarantine mandate due to Covid. Our first use case addresses the practical need to physically reorganize the interior of the dwelling place to accommodate a myriad number of human activities, while the second use case captures the desire to escape the confines of the dwelling space by reorganizing it to evoke "other places" outside its walls.

1) Use Case 1: A Robot-Room Serving Practical Needs: "They Remodeled Before Covid. Here's What They Regret Now," January 14, 2022 [8]. Pre-pandemic, the architects for a loft remodel in New York City allocated one-third of the loft's space to work activity, two-thirds for family life. This allocation worked well at the start of the pandemic "when the grandchildren often visited, using the open living space as a playroom"; but soon, "desperate for more space and quiet, … the 4-by-7-foot closet in the guest room" became an office entered by ducking under a beam. In this closet-office, "there were days when Mr. Uriu was on the phone trying to salvage his business …, while Ms. O'Mara was trying to keep the attention of children as she taught art classes over Zoom, separated [from Mr. Uriu] only by Soji screens." This provides motivation for a robot-room, adaptive to changing programs, serving practical needs.

2) Use Case 2: A Robot-Room Serving "Escapist" Needs: "How to Escape Without Leaving Your Home," October 13, 2020 [3]. The concept here is sensible: "If you think about escaping as a way to give your mind some time to reset, rather than seeking out a new physical space, you can find respite without going outside." The author then offers "seven strategies for creating an oasis at home"; however, all but one of these strategies requires "set[ting] up and tak[ing] down ad hoc," like a "side-street café." This provides motivation for a robot-room, a portal to "other places," serving escapist needs.

These two, real-world scenarios selected from The New York Times currently serve as our two use cases for testing robot-room prototypes.

IV. Human Centered Design Study

Our team identified eight spatial configurations achievable by our robot surfaces (scaled to be ergonomically correct) (Fig 7) and seven domestic activities these configurations might support. The human activities are: A) eating dinner with family, B) reading to children, C) watching TV with partner, D) napping, E) taking a video call, F) (no explicit activity), G) conducting an online (Zoom) meeting, and H) working on a computer.

We conducted an online survey of 52 questions to explore the robot room's applications for future design iteration. In the 80 respondents recruited via the Prolific research platform across the US, Canada, and EU countries, we ended up with 77 participants (37 females, 38 males, two non-binary, age M=29.7 years) having passed all three "attention-check" questions of our survey. 47 of them reported owning at least one smart device.

Within the survey, we tasked participants with selecting the most suitable activity and next-ranked activities from the seven identified above for each of the eight configurations. We also instructed them to undertake the reciprocal task, matching the eight configurations to the seven activities. Additionally, we assessed user understanding of our two early prototypes reported here using static images and GIFs.

A. Survey Results

	A	B	C	D	E	F	G	H
Eat dinner with family	11	8	6	10	2	1	2	18
Read to children	1	11	4	1	11	4	3	4
Watch TV with partner	7	22	16	11	18	19	12	11
Take a nap	3	16	37	48	6	47	4	1
Take a video with friends	7	8	4	0	6	2	27	6
Have a business meting	2	4	2	3	6	2	21	4
Do work on a computer	46	8	8	4	28	2	8	33

Fig. 5. Table depicting the most selected activity for each configuration, resulting from questions, "Which activity would you most like to do with the furniture "shape-X" shown below?"; Red: the research team's hypothesized selections; Yellow: the participants' actual selections.

1) Matching Configuration and Activity: Fig. 5 shows a table of the preferred activities matched to the eight configurations. The red cells highlight the activity-matches hypothesized by the research team, while the yellow cells highlight the activity-matches selected by the participants. Except for D and H, the two sets of selections were discrepant. Moreover, we observed a high concentration of activity selection: "take a nap" and "do work on a computer" were predominantly selected for three of eight configurations.

Similar results were found with our reciprocal questions: preferred configurations matched to activity. The table in Fig. 6 exhibits the most preferred configurations selected for the seven activities. The red cells highlight configuration-matches hypothesized by the research team, while the green cells highlight the matches made by participants. Configurations E and H were most selected for, respectively, three and two of the even activities.

	A	B	C	D	E	F	G	H
Eat dinner with family	21	10	2	10	3	1	3	27
Read to children	1	4	10	5	26	19	1	11
Watch TV with partner	0	6	7	3	11	48	0	2
Take a nap	0	0	4	55	0	17	1	0
Take a video with friends	6	4	2	2	31	16	7	9
Have a business meting	6	0	2	0	10	5	4	50
Do work on a computer	12	2	0	3	13	3	0	44

Fig. 6. The most selected configuration for each activity, resulting from questions, "You would like to do…. Which of these space designs best accommodates this activity?"; Red: the research team's hypothesized selections; Green: the participants' actual selections.

2) User Perspective of Two Early Prototypes: Within the survey, participants viewed GIFs of two prototype transformations and static images of five configurations they shape as shown in Fig. 3 and 4. They were then asked to select the activities they judged most supported by these configurations and rank the preferred means for controlling the robots. A significant 81.8% of respondents identified the transformation of prototype A as a transition "from a lounge chair to a bed," and 80.5% of participants believed in A's capapcity to support activities ranging from watching TV to taking a nap; both observations echoed the researchers' design objectives. Unlike the relatively unified perception of prototype A, the

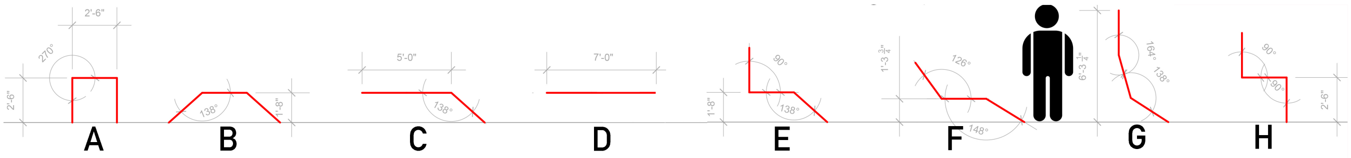

Fig. 7. Eight spatial configurations of a 7'-8" three-segment robot surface with a 5'-7" figure

Configuration Adjustment Methods	Prototype A	Prototype B	Ranking
Remote control the robot room to adjust.	2.29	2.36	1
Voice commands the robot room to adjust.	2.71	2.91	2
Adjust the robot room by using an iPad app.	3.14	3.17	3
Physically adjust the robot room myself.	3.36	3.21	4
Gesture the robot room to adjust.	3.94	3.88	5
Let the robot room adjust itself where it decides I want it.	5.56	5.47	6

TABLE I

THE AVERAGE RANKINGS OF CONFIGURATION ADJUSTMENT METHODS AMONG SIX OPTIONS, RESULTING FROM TWO SEPARATE QUESTIONS, "IF YOU WANT TO ADJUST THIS ROBOT SURFACE (A/B) PHYSICALLY – MAKE IT CHANGE INTO ANOTHER FORM YOU WANT – HOW WOULD YOU LIKE TO DO THIS? (1 FOR YOUR "MOST FAVORITE" AND 6 FOR YOUR "LEAST FAVORITE")"

Statements	Prototype A	Prototype B
I think I would like this robot surface in the future.	2.84	2.66
I understand how this robot surface might help me.	3.34	3.03
I understand how this robot surface works on a basic level.	3.91	3.49
This robot surface will help make routine tasks easier to perform.	2.90	2.62
I could envision this robot surface in my living space.	2.83	2.55
This robot surface will make daily chores fun.	2.66	2.44
This robot surface could be applied to many of my domestic activities.	2.94	2.58

TABLE II

THE AVERAGE SCORES OF TWO PROTOTYPE ASSESSMENTS, RESULTING FROM TWO SEPARATE QUESTIONS, "AS SHOWN IN THE GIF (A/B), THIS ROBOT SURFACE CAN TRANSFORM INTO VARIOUS SHAPES. FOR EACH OF THE FOLLOWING STATEMENTS, PLEASE SELECT THE NUMBER THAT REPRESENTS HOW YOU FEEL ABOUT THIS ROBOT SURFACE. (STRONGLY DISAGREE 1 – STRONGLY AGREE 5)"

views on prototype B's transformation were more divergent. 46.8% of participants saw it as a transition "from taking a nap to watching TV," whereas 45.5% considered it a shift "from doing computer work to reading a book." Prototype B, showing three stages of reconfiguration, was deemed to be optimally suited for three different activities: computer work, relaxation (Fig. 4B), and TV watching (Fig. 4A).

3) Comparison between Two Early Prototypes: Participants, when asked by which means they would control prototypes A and B, preferred remote control and were averse to full autonomy, for both prototypes (Table I). Participants meanwhile somewhat preferred prototype A over B (Table IV-A.3), finding A easier to understand and potentially more helpful to them. While A is the preference, we recognize the design and prototyping work reported here is early yet adds to our prior efforts (referenced here) developing tendon and McKibben actuated robot surfaces. These survey results will help inform which of our actuation approaches, in which combinations and numbers, we further advance, and how we control them, as we realize a full-scale robot room.

B. Further Discussion of Survey Results

	A	B	C	D	E	F	G	H
Eat dinner with family								
Read to children								
Watch TV with partner								
Take a nap								
Take a video with friends								
Have a business meting								
Do work on a computer								

Fig. 8. The overlaid table of Tables 1 and 2. Red: the research team's hypothesized selections; Yellow: the participants' actual activity-to-configuration selection; Green: the participants' actual configuration-to-activity selection.

1) Discrepancy between User's and Researcher's Selections: The discrepancy between the hypothesized and the actual configuration-human activity matches are summarized in Fig. 9. While our research team initially envisioned discrete configurations matching singular domestic activities, the survey results suggest that people envision each of our configurations supporting multiple and other-than-expected activities, a finding that will inform our subsequent design activity.

2) Maximize User Benefits with Minimal Engineering Efforts: Asked to match activities to configurations, we classified as "suitable" activities (highlighted in blue in Fig. 9) any activity-match selected by at least 35 out of 77 participants; those activities that received fewer than 15 selections were labeled "unsuitable" (orange). This categorization helps clarify for us how well configurations-activities are matched.

	A	B	C	D	E	F	G	H
Eat dinner with family								
Read to children								
Watch TV with partner								
Take a nap								
Take a video with friends								
Have a business meting								
Do work on a computer								

Fig. 9. The classification of suitable and unsuitable activities, resulting from questions, "What other activities do you think shape-X can support?". Blue: "suitable" activities"; Orange:"unsuitable activities" .

As shown in Fig. 9, configurations F and H emerged as the most versatile, each deemed apt for four activities. Further, a combination of configurations F and H or D and H could comprehensively support seven activities. While configurations F and D were associated with more "relaxing" activities such as watching TV and taking a nap, configuration H was perceived as aligning more with productive purposes, like having a business meeting and doing computer work. The fact that the pairs F-H and D-H accommodate the seven activities might suggest participants' inclination to categorize domestic activities as either "relaxing" or "non-relaxing" in the context of robot configuration.

This revelation presents a development opportunity to optimize user-centered solutions with minimal engineering efforts - a key contribution of the work reported in this paper. From a user perspective, our results suggest that a robot room spanning eight configurations, A to H, might be just as helpful as a robot room that solely supports two configurations F-H or D-H, while the latter significantly reduces engineering investment. For our research team, the results of our online survey informed a next iteration of the prototypes reported here (as shown in our video supporting this paper) and suggest that we might focus future robot room development on the F-H or D-H transformation. For the larger robotics community, our survey findings highlight the importance of human user insights during the earliest stages of robot development. Generalizing from our case, there are unexpected things to learn from user study participants that may steer the trajectory of robotics research to more responsibly support and augment real world scenarios of concern to "real world" people.

V. Future Work

We will next conduct a User Experience (UX) study to investigate the experiences of participants interacting with prototypes representing the two robot-room concepts. This UX study will be conducted in-person using full-scale, rapid prototyping as accomplished successfully in previous research by our team (e.g., in [5]). The goals for the UX Study are to: (a) identify strengths and weaknesses of each of our robot-room concepts; (b) determine users' satisfaction with alternative manifestations of each of the two robot-room concepts; and (c) characterize experience to clarify what is a robot-room, communicated as design guidelines. Ongoing iteration of a robot-room prototype will be informed by cycles of evaluation with respect to its usability, performance, and efficacy. Characterization of the robot-room will contribute a foundational understanding of space-making robots for the research community to build on.

VI. Conclusion

We discussed the motivation for robot rooms, presented early prototypes of robot surfaces that, in multiples, might form them, and reported on a user study where participants made matches of robot configurations of our prototypes and human needs and wants of a robot room. One interesting finding from our online study is that, overwhelmingly, participants reported not wanting the robot surfaces (that make a robot-room) to function autonomously. It seems that in everyday, unstructured spaces, people can live with AI confined to computer screens or Amazon Echos but not embodied in a physical robot - something for the field to seriously ponder. Ultimately, we expect the robot-room will prove an impactful form of human-robot interaction whereby the machine physically envelops people, extending HRI beyond current conceptions of productivity and play.

Acknowledgments

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