Design and Characterization of a Novel, Continuum-Robot Surface for the Human Environment

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***Abstract*—We present a novel, robot form 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. We introduce such a robot, a novel, tendon-driven, continuum robot surface we call a "Space Agent." This paper presents our concept, design, and realization of the Space Agent. 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. We found a validating match between prototype and simulations for the five configurations investigated. The paper 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],[2]).

Meanwhile, the development of robotics for the built environment has mostly focused on fabricating conventional buildings using industrial robots [3] and not on embedding robotics in the physical environment—what we call *architectural robotics*, (an expertise of the authors; e.g. [4]). Further, the development of assistive robotics for use in the everyday spaces we live in—the home, hospital, school, and office—has been primarily focused on humanoid robotics as replacements for human servants (e.g. [5]), rather than supporting and augmenting human capabilities through a co-operative *environment* [6],[7]. Nevertheless, the increasing embedding of technology in the physical environment, the intensified developments in human-robot interaction research, and the number of potential use cases for cyber-physical environments warrant an expanded focus of the robotics community on robot surfaces that literally and figuratively shape the places in which we live, work, learn and play.

Fig. 1. *Space Agent*—a space-making (continuum) robot surface.

We call such robot surfaces *Space Agents*, malleable, adaptive, physical surfaces that are dependent on some form of actuation and automation to arrive at a variety of shape-shifting, functional configurations that support and augment human activity in ways perceived as familiar. More practically, a Space Agent 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. As Space Agents actively expand the affordances of conventional rooms and transform the most confined spaces into, effectively, "many rooms" and are capable of some manipulation tasks, Space Agents have applications in wide-ranging environments: assisted care and hospital facilities, schools, housing and offices in costly real estate markets and, in the future, in spacecraft/space habitation and the interiors of fully autonomous vehicle. For such wide-ranging applications, Space Agents are envisioned as reconfiguring physical spaces in response to the expressed needs of an environment's occupant—*Space Agency*.

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This work was supported in part by the U.S. National Science Foundation under grants IIS-1527165 and IIS-1718075.

Space Agents won't 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 Space Agents: (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 our 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) [8].

TABLE I. FIVE "CAPACITIES' OF THE ROBOT SURFACE

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

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 our novel robotic surface, we briefly review three prior, foundational efforts in this research domain, including two from our own group, to make evident the advances of the reported effort. These foundational efforts were considered in greater detail in our previous published work [9],[10],[11] predating the *Space Agent* prototype.

Fig. 2. (A) *CompResS*, (B) *MuscleBody, and* (C) *AWE.*

Our *CompResS* (Fig. 2.A) [11] is a shape-making, surface robot capable of reconfiguring itself. While novel, *CompResS* is limited in the number of configurations it can accomplish, it can be difficult to control, and it can only accomplish the goal of space-making [11]. *MuscleBody* (TU Delft, 2005; Fig. 2.B) [12] is a bulbous, McKibben-actuated volume that can accommodate several inhabitants who, by their actions, cause shape transformations. The *MuscleBody*, however, cannot be precisely controlled. Our own *Animated Working Environment* or "AWE" (Fig. 2.C) [9],[13], reconfigures itself to support specific human activities focused on collaborative work. AWE is distinguished by its capacity to precisely configure a physical space to support human activity; however, its planar form only reconfigures in one dimension—not two, which affords more nimble, nuanced space-making.

IV. SYSTEM DESCRIPTION AND CHARACTERIZATION

Our 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],[14]**.** 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],[4],[9],[10],[11], the *Space Agent* surface represents a novel contribution to robotics not realized previously.

A. *Theoretical Approach*

To inform our development of the Space Agent, we studied the design and behavior of social robots in various environments, such as robots in homes [5],[15] and in healthcare [16],[17] with special emphasis on how human beings may be assisted by robots in activities of daily living [18] as well as tasks in work environments [19].

We envision Space Agents embedded within the surfaces of a room's ceilings and walls, and offering three specific behaviors: *space-making, manipulation, and gesture-making*. Our prototype (Fig.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 [20]. 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. Fig. 3 illustrates three variations of tendon-driven robots of our own design [11],[21-23] that informed the Space Agent.

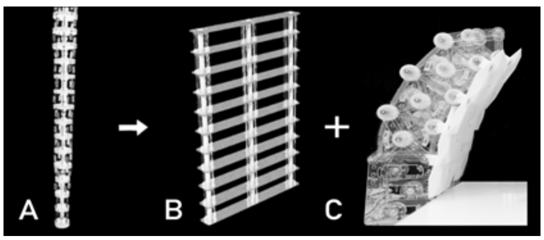

Fig. 3. Tendon-driven surfaces from prior work.

B. *Development of Agent Variations*

In developing our tendon-driven surface, we 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, we considered a wide variety of tendon numbers, arrangements, and termination points. We also considered surfaces of different materials of singular and composite construction with different physical properties (e.g. stiffness, density, etc.) [20]. 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.

Beyond the physical structure of the *Space Agent* prototype, we considered the mechanisms by which the robot may be controlled by humans and may interact with humans in a given environment. Thus, we are exploring the inclusion of: touch sensors on the surface; transducers to enable haptic interaction (as in [24]); RGBD sensors to enable gesture commands [25]; voice control [26]; and other control mechanisms.

C. *Prototype Design*

Fig. 4 shows the reconfigurable, tendon-driven Space Agent 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. The foam used for the prototype is a white polyethylene foam supplied by *New England Foam* (USA) [27]. 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 Space Agent design, the number of tendons and arrangement, as well as where the tendons were attached would greatly affect the configurations the Space Agent 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 our purposes as it could be accurately modeled kinematically (section IV) and reconfigured to adequately achieve the desired configurations.

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 space agent (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.

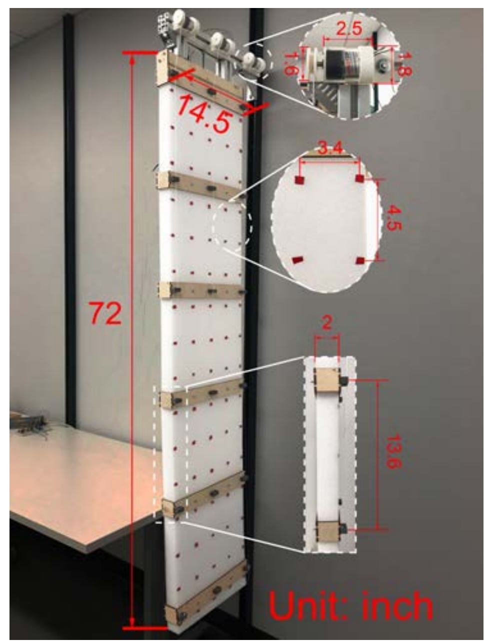

Fig. 4. Dimensions of the built prototype.

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).

D. Electrical Hardware Design

Above the mount of the *Space Agent* 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

The resulting composite structure of the prototype (Fig. 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 our supporting video).

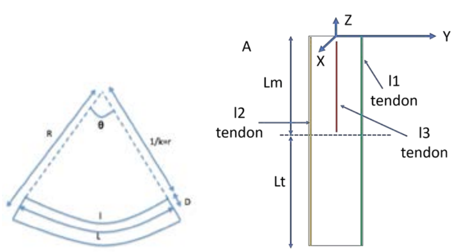

Fig. 5. Labeled variables (A) *Curvature,* (B) *Dimensions*

V. Kinematic Model

In order to model the configurations of the *Space Agent*, 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 [28]. This was done using the relations between angle, arc length, and radius with the variables shown in Fig.5(A) which depicts a schematic side view of the surface, the bend angle, and curvature. Fig.5(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 $l_3 \in \mathbb{R}^+_0$ controls the bending up to the midpoint of the surface. Due to the way tendons are 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 width w 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

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

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

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

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).

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

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

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 for l_k in (3b).
Solving (3) gives us the curve parameters

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

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.

$$\mathbf{T}_k(y, l_1, l_2, l_3) = \mathbf{P}_y(y)\mathbf{P}_x(\lambda_k)\mathbf{R}_y(\theta_k)\mathbf{P}_x(-\lambda_k) \quad (5)$$

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

We conducted an analysis of the shape-making capabilities of our surface prototype. For this, our 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 our 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, we 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 our Space Agent was developed using MATLAB. In Figure 7, top row, the simulation shows various, configured shapes of the Space Agent. 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*

We utilized a *Microsoft Kinect* camera [29],[30] 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 [31]. We 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 [31],[32]. 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 we wanted to capture data, we marked the surface of the space agent with distinct, contrasting red-tape markers as seen in Fig. 1 and Fig. 4. 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.

The *Kinect* was able to collect data for 75 evenly spaced points. An output image of the depth at each marked point on the surface at a rest configuration can be seen in Fig. 6.

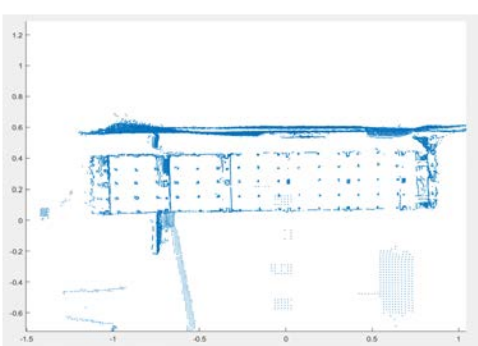

Fig. 6. *Kinect* RGB-D Output Image of (1) *Rest* Configuration.

C. *Experimental Design*

We investigated whether the physical robot surface we 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.

We 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 our supporting video. Once each configuration was achieved, we 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*

TABLE II. SUMMARY OF RESULTS

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

When observing the transition of the *Space Agent* between each configuration, we found that the design quite successfully allowed for smooth transitions, regardless of the start and end configuration. We also noted from our observations that the physical prototype convincingly assumed the desired configurations (Fig.7, bottom row) that were also achieved in the simulation (Fig.7, top row).

In order to compare the physical experiments to the simulation, we calculated the percent error between the experimental, Kinect-captured three-dimensional locations of the marked points and the corresponding points in the simulation. Table II summarizes the results of the experiments versus the simulations for the five configurations. A smaller standard deviation of the percent difference across the surface

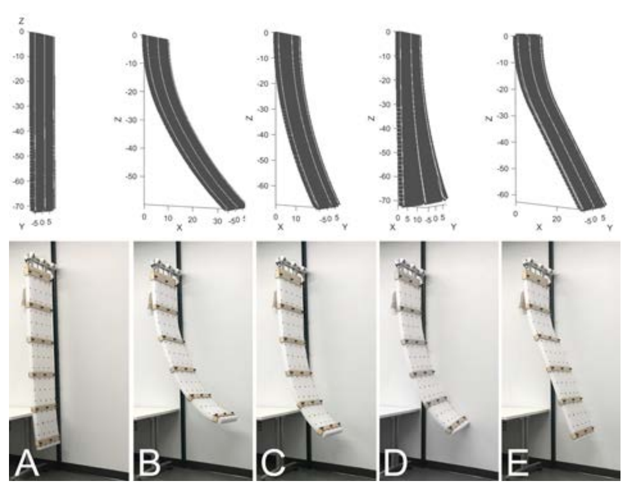

Fig. 7. Top Row: Simulation of 5 Configurations, Bottom Row: Prototype Images of Configurations.

indicates a higher degree of consistency in relative positions, meaning the Space Agent 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 our testing of each configuration, and from deviations between the measured configurations and simulated configurations, that the surface of the Space Agent 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 our expectations.

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 [32]. 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.

In sum, the results suggest validation between the experiment and simulation configurations: the Space Agent 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 human-robot interaction investigations involving a variety of design tasks, use case analyses, and user studies to iterate the design for successful human-robot interaction in a variety of environments, including a fully autonomous vehicle interior (Fig. 8).

A. Prototype Iterations

In this paper, we explored the characteristics of a 2" surface. Future prototype iterations will explore varying degrees of thickness and alternative materials to better characterize how materials affect dexterity [20] and the capabilities of a surface robot. Further, enhancements can be made to the design of the collars to ensure they more effectively guide the tendons and bending of the surface without inhibiting reconfigurability. This can easily be accomplished by decreasing the thickness of each collar. The prospect of smaller space agents can also be explored to understand how varying surface sizes can assist humans differently in unique environments.

Fig. 8. Space Agents as envisioned inside an autonomous vehicle.

B. User Studies of Human-Robot Interaction

Future work on the *Space Agent* 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. User studies will include observations, interviews, surveys and suggestions. Feedback from such user studies will illustrate how the Space Agent can best be iterated to accomplish its targeted human-assistive capacities. We also hope that user studies will help reveal how users prefer to interact with the surface robot. This 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." We aim in these studies to demonstrate how surface robots can meet the needs of humans and extend the capabilities of the workplace environment.

C. Methods of Human-Robot Interaction

In order to better enable the Space Agent to assist humans in the five capacities, the robot surface must be able to respond to the needs and input of its user. We eventually plan to use both sensors and machine learning to realize interactive and intelligent control of the built environment.

In an effort to determine the best methods of interaction and control by users, our lab group has already begun exploring the integration of various methods of user interface. For example, we are developing a graphical user interface in Unity [33] (a game development tool), integrating voice control via Amazon's Alexa technology [26], integrating touch sensors for direct control [34], as well as cameras with the ability to capture and respond to human motions [29].

IX. Conclusion

We 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. We presented the core concept, design, and realization of a physical prototype. We found that, for five distinct, "typological" configurations of the robot surface, there was a reasonable match between our 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.

Acknowledgement

The authors thank Chase Frazelle of Clemson University for his work on the color-and-depth recognition Kinect program for MATLAB.

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