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A Continuum Robot Surface of Woven, McKibben Muscles Embedded in and Giving Shape to Rooms

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Abstract— **Robots are typically designed as occupants of rooms, adapting to, and navigating within them. "Robot surfaces," an emerging robot typology, are not occupants of but *integral* with rooms, physically shaping rooms to support human activity. We report on an advancement of robot surfaces formed by weaving McKibben Pneumatic Air Muscles that, when actuated, morph a 2D planar surface to generate 3D geometries including a "spherical cap." Following our foundational study at different scales with different materials, we developed a full-scale prototype that offers an intimate and private space for people meeting in open plan environments. We report on our research, focusing on a design case, and validate the full-scale prototype as compared to our Non-Uniform Rational B-Splines (NURBS) model for three useful configurations. Our quantitative and qualitative results suggest that our robot surface can support human activity as envisioned. This research contributes foundational understanding of an emerging category of robotics from which our team and peers can build.**

I. Introduction

Robots operating inside a building are typically designed to be occupants of that building, adapting to the building's interior and traversing and navigating through specific points within that given, physical space. "Robot surfaces" take a different approach: they are 2D robots *integral* to building interiors, mounted on, or embedded in ceilings and walls. In concept, such morphing 2D robot surfaces generate 3D geometries that can actively shape rooms and afford new functionality matched to unfolding human activity within these rooms.

We envision robot surfaces functioning in both open-plan spaces like hotel lobbies and confined spaces like micro apartments and offices (Fig. 1). But no matter what the room size, robot surfaces can make a physical space multi-functional in support of human activity over time, providing a more intimate, private human experience.

There has been relatively little research on the development of robotic surfaces. Some efforts have concentrated on the development of sensor skins, as exemplified in [1], [2], and garments with embedded sensors [3]. In work more related to that reported here, efforts have concentrated on the physical design of morphable surfaces [4] as well as the embedding of actuators in active textiles [5]. In designing, modeling, and prototyping 2D continuum surface robots, our research team aims to make them robust, scalable, compliant, and inherently safe during physical interactions with humans. In our early work on robot surfaces, we developed simple, continuum robot surfaces, inspired partly by existing continuum robot arms (e.g., [6-9]) including a novel pinecone-inspired, tendon–actuated surface [10], a simple surface of McKibben muscles (also known as Pneumatic Air Muscles or PAMs) [11], a simply tendon-actuated surface [12-14], a hyper-redundant, rigid-linked surface [15], and a hinged surface inspired by origami [16]. These prior efforts represent only a beginning: continuum-robot surfaces are a relatively unexplored concept and represent a new and novel contribution to robotics.

Figure 1. Our vision of robot surfaces as a dynamic canopy and tablet.

The shapes generated by our previous efforts were limited to bending and twisting of an extended plane (as shown in Fig. 1) which suffices for some applications; however, we had not (previous to the effort reported here) achieved a configuration that is bowl-like—the shape of an umbrella or the shape you make with your two hands to capture water, formally known as a "spherical cap." A 2D surface that can configure as a spherical cap is capable of enveloping space in a way that a bending and twisting plane cannot. To achieve this complex surface behavior—reported here for the first time—we designed, prototyped (at full-scale), and evaluated a continuum robot surface of woven and interleaved McKibben muscles that can configure a spherical cap as well as the bending and twisting behaviors of our prior efforts. Such a surface exhibits formal possibilities that have a high degree of utility and functionality in "giving shape" to human activity unfolding in rooms over time. This "spherical cap" behavior was accomplished by applying fundamental weaving techniques in elaborate patterns over a continuous flexible medium.

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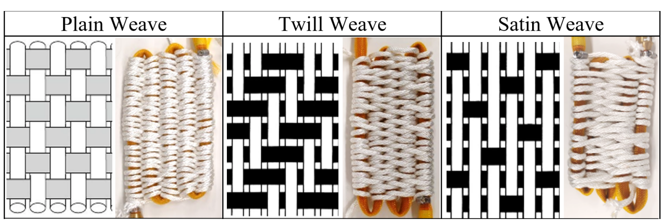
In theory, the surface geometries generated by robot surfaces are comprised of different combinations of curvatures and sinusoidal patterns. Weaving patterns can be interwoven to create surfaces that have a high level of customizability and modularity. Combining these patterns affords them to be used for wide-ranging applications. For the effort reported here, we identified one likely application as a test case: robot surfaces shaping a large, open-plan room—specifically a hotel lobby (but it could be an airport terminal)—to support and augment the human activity within it. Hotel lobbies can be vast open spaces of multiple programs (reception, bar, restaurant). Is there a dynamic way to "give form" to these different programs, adapting to changing programs (for a wedding reception or a conference meeting)? Our research explored this question by firstly developing a foundational design, and secondly designing for a specific application.

II. Foundational Design

Foundational design consisted of fabrication and characterization of surfaces using different substrates and weaving patterns. The goal was to identify and quantify a series of heuristics that could be used in the future to aid in the creation of large-scale woven robot surfaces. Throughout our series of experiments, we tested several different variables regarding the surfaces including the weaving method, alternative substrates, and different weaving densities.

To create a surface that can achieve the envisioned complex, two-dimensional mutability for rooms inhabited by busy people, we elected to use McKibben muscles as informed by our prior efforts. As compared to a tendon-actuated surface (as in our [12-14]) or an origami of hinged, rigid panels (as in our [16]), McKibben muscles make for a compliant surface that is relatively safe when in proximity to people engaged in wide-ranging activities. Further motivations for using McKibben muscles in robot surfaces are that they are robust and can be relatively silent when the compressor is part of the building's servicing, fed from a distance.

Figure 2. Foundational weave patterns explored where the left shows diagrams adapted from [17] (with white being the warp and black being the weft) and the right shows our exploration of prior work using McKibben actuators as the warp and nylon string as the weft.



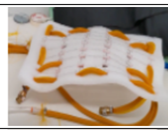
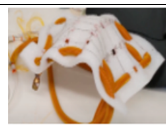
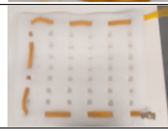
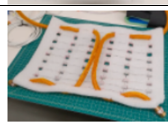
With McKibben muscles as the selected actuator, we had to determine a way to integrate them into the surface's substrate. One way to seamlessly integrate actuators in a substrate is to structurally organize them following established textile techniques which offer the capabilities of stretch and strain to produce the complex motions and geometries we sought [17]. Previous work done in creating PAM actuated textiles using techniques such as braiding [18] and weaving [19] used very thin McKibben muscles that expanded and contracted to deform a textile surface at a very small scale (in/cm versus ft/m) [20]. In other prior work, McKibben muscles were the warp—the longitudinal set of the weave—as opposed to the weft which can afford the flexibility to be woven and interlaced through the warp (Fig. 2).

After multiple experiments, we chose the latter option, PAMs as the weft: the PAMs of our design are woven through a substrate that acts as the warp. Following this option, we experimented with various weaving techniques as shown in Fig. 2. While McKibben muscles have proven to be stiff and bulky for some small-scale applications of active textiles, we were able to apply these techniques at the larger scale so that these negative characteristics became advantageous in generating enough contraction without hampering the behaviors of the surface due to excessive bulkiness.

To weave the surface, we experimented with various materials, alone and in combinations, including PAMs, nylon rope, and elastic cord. Rope is extremely malleable and when actuated, the surface could be easily shaped. Elastic cord proved too stiff and would not deform when under actuation. When actuators were woven together in both the warp and weft, we found that the surface formed would become extremely stiff and compact but failed to deform or bend. We also tried different weave patterns that vary how easily-shaped the surface was, based on how tightly patterned the weave was. The different weaves applied were a plain weave, variants of a twill weave, and satin weave ([21], see Fig. 2). A plain weave produced the tightest pattern. A twill weave was not as tight. as the weft goes over and under the warp fewer times. A satin weave was looser yet. In our experiments, we found that the looser the weave, the greater the surface bent. The pronunciation in curvature follows from the orientation of the actuator relative to the surface. When the actuator is normal to the surface, a more pronounced curvature is achieved due to a minimum in substrate stiffness in this orientation. A denser weave leads to more parallel sections between the surface and the actuator, which causes less pronounced curvatures due to the more prominent substrate stiffness. In addition to these design approaches, we also tried several unconventional patterns of weaving, specifically interlacing the McKibben muscles into a base substrate. Table 1 presents all these patterns, both the established and novel ones, with photos of the robot surfaces achieved, shown unactuated and actuated. The sine wave curve is one iteration of a plain weave and is applied in varying orientations and lengths using one actuator. The other geometries are achieved from combinations of actuator placements. Notice that while some geometries can be created with less actuators (such as the saddle created with only one actuator in the middle), plain weaves are often added to give form and rigidity to enhance the geometry.

Substrates used in our foundational design included cloth, corrugated plastic, and foam. We found that cloth would too quickly bunch up under actuation, while corrugated plastic proved to be too stiff. By laser-cutting slits in or scoring the corrugated plastic surface, bending was attained but the surface was striated rather than smooth. Our selected substrate was a 1" thick, 1.7# density polyurethane foam that had the stiffness to maintain its shape under actuation that was sufficiently malleable to deform, and that could return to its original shape with minimal residual creep. Weaving with the actuator as the weft through a foam substrate yielded more complex behaviors that we envisioned could apply to the hotel lobby application (i.e., design use case).

TABLE I. GEOMETRIES AND UNCONVENTIONAL INTERLACING METHODS

Name	Description	Unactuated Surface	Actuated Surface
Sine Wave Curve	Actuator goes through a central axis through the surface.		
Bowl	Two perpendicular sine wave curves on top of one another.		
Cup	Curvature is achieved through a plain weave on perimeter.		
Saddle	A plain weave on the sides of the saddle; actuators in the middle.		

III. Design for a Specific Application

In the foundational design phase, we selected an actuator and explored various materials with which to weave, various weaving patterns, and various substrates. To further focus our experimentation, we advanced the design of a robot surface specifically for the use case—a hotel lobby application (Fig. 3). We envisioned a familiar hotel lobby scenario whereby two to four people agree meet in the lobby, arrive and find each other, and then move to lobby seating for the duration of their meeting. Robot surfaces mounted on the ceiling above a group of seating elements (chairs, sofas) could then gently descend to define a more private space for this intimate meeting of friends, family, or business associates. We might imagine that, during such a meeting, one member of the party needs to slip away to take a phone call; this human requirement is facilitated by one of the robot surfaces twisting to permit this passage.

Following from this familiar hotel lobby scene and its associated design requirements, we envisioned ceiling-mounted robot surfaces situated in an array, like petals of an upside-down tulip. When no one is seated beneath them, the petals would assume a slightly curved or horizontal (planar) configuration with the flat ceiling lying just above them. When seating is occupied, the "petals" descend and curve to shape a space around the group. Rather than creating a flower design that requires one continuum robot surface for the "tulip," we took a modular approach, letting each petal be its own continuum robot surface. With this design, the number of petals can easily be reconfigured for various purposes and localized actuations. Petal dimensions of 4.5'-wide and 6'-long were determined by a typical coffee or casual dining table of 30" diameter that commonly sits at the center of hotel seating. We also needed to accommodate people of wide-ranging heights so that they can walk under the structure. Hotel lobbies typically have high ceiling heights that accommodate this design requirement.

A. Configurations

Four surface configurations were defined based on the use case just described. *Configuration-1 (Most-Upright—essentially the "resting" state of the surface):* the surface is most elevated for when individuals are seating themselves. This requires the surface to be stiff throughout so the actuator that goes about the perimeter is pressurized. *Configuration-2 (Fully Actuated)*: the surfaces are curved, defining the space around the group of seating when everyone is seated. This provides an element of privacy, atmosphere, and defines a socially distanced space. Here, all actuators are engaged so that the structure maintains a closed position. *Configuration-3 (Open to the Left)*: one petal allows one individual to exit the group (e.g., momentarily to take a phone call). Instead of having the whole petal lift-up completely, the pressure in only the left side of the petal is reduced, causing the left side to become not as curved, allowing for an adequate gap for someone to "slip out" of the group without much disruption. *Configuration-4 (Open to the Right)* is like Configuration-3 but applied to the right side.

B. 3D Model Design of the Robot Surfaces

A 3D model was created using Computer Assisted Design (CAD) software for each of the different configurations the surface was expected to assume (e.g., Fig. 3). A sketch of the surface was created in Autodesk: Fusion 360 using two-dimensional non-uniform rational B-splines (NURBS). Using the locations of our control points, the sketch was then recreated in Rhino 7 where it was made into a surface. The surface was then populated with three-dimensional control points. These control points were used to create the idealized model. Due to the choppy nature of the model created, from the discretization of control points, a "smoother" was applied to gain a less striated surface, justified by an aim to create large swaths of controlled curvature while minimizing any unwanted sinusoidal patterns (Fig. 4). This model served as the goal and main point of comparison throughout testing as will be reported here, below.

Given our 3D model, we sought to balance the number of petals required to minimize mass while maintaining both the

Figure 3. Open-plan hotel lobby design case: *Left*—a rendering of the robot surfaces elevated and curved downward when people are not seated and seated respectively; *Right*—the full-scale prototype: Two people meet (A) and seat themselves (B), at which point the surface descends and curves (C), "Fully Actuated." After some time, a member of the party needs to excuse himself for a phone call; the surface "Opens to the Right" (D to E).

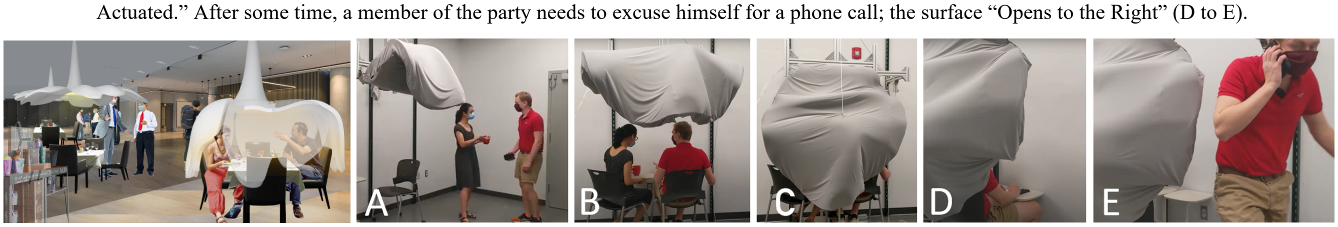
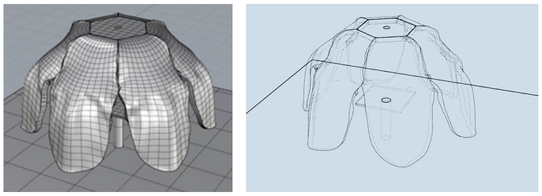


Figure 4. The NURBS model of robot surface and table inside: *Left*—opaque view; *Right*—transparent view.



visual appeal and the definition of the meeting space. Several alternative numbers of petals were considered for our design: 4, 5, 6, and 9. We determined the numbers of petals for our design by how well each assembly meshed to define space (i.e., the length of the shared side between petals). As the number of petals increased, so did the length of the shared side increase. Additionally, our larger research group assessed the visual appeal of assemblies of different numbers of petals. We ultimately arrived at six petals for our constructed design.

C. Actuator Designs

For the robot surface, we fabricated our own McKibben actuators. These consisted of 50A durometer silicone tubing with an outer diameter of ½" wrapped in a woven polyester expandable sleeving. At one end, we connected the actuators to a pressure supply via push-to-connect adapters; at the terminal end, the actuators were enclosed with a 45-degree, flared brass, short nut-and plug assembly. These actuators could withstand pressures over 60 psi. Throughout design and testing, a pressure of 60 psi was used as the maximum operating pressure. This was due to pressure control limitations from the pressure regulators we used.

D. Prototyping Small to Medium to Full Scale

We studied prototypes "small" (12" wide x 19" tall), "medium" (19" x 29"), and full-scale (54" x 72"), dimensioned according to a width-to-heigh ratio (.63 to .66 to .75) adapted to design criteria. The small prototype was made up of one continuous piece of Styrofoam, while the medium and full-scale prototype were constructed with two pieces (19." x 14.5" and 54" x 36" respectively). From the smaller prototypes, we learned that the surfaces should be secured by zip ties in addition to adhesives due to multiple iterations of testing.

For the full-scale prototype (Fig. 3 *Right* and Fig. 6), we fabricated and studied one petal. After cutting the Styrofoam to the correct shape of the petal, 1"x1" sized squares were cut into the foam surface for the actuators to be woven through. The final design of the actuator array consists of a pair of 16'-long actuators on the extremes of the petal, a pair of 3'-long actuators that create the gap (for someone to "slip out"), and two actuators of 9' and 13' lengths to lift the structure. "Length" here is the length of the gauze portion of the actuator. After the actuators were constructed and woven into the Styrofoam, softer foam was put on each side of the surface to create a smooth finished surface when cased in sewn, knit, stretch jersey fabric that allows the entire petal to maintain its structure and morph.

Due to the increased weight, the actuators proved too weak to generate extreme displacement, (i.e., > 5 feet). Because of this, an alternative form of actuation was needed to move from Configuration A to Configuration C (see Fig. 3). The method employed was a single pulley attached to the direct center of the petal Styrofoam layer. This pulley was solely used to hinge the petal from the "raised" configuration to the "lowered" configuration, not to shape the surface.

E. Weaving Pattern

From the small to the medium to the full-scale prototype, we experimented with actuator placement design through trial and error in empirical testing. As shown in Fig. 5, the placement varied greatly across scales due to the challenge of scaling-up while using the same cross-section of McKibben muscle. As might be expected, the placement of three actuators for the small prototype was insufficient in the medium prototype to both form the curve and lift it as we wanted; as such, the medium prototype required a fourth actuator across the center of the surface. The full-scale prototype, likewise, required a redesign of the actuation.

For all three prototypes, the actuators on the perimeter dedicated to curving the petal remained a constant in the design, as it also provided rigidity. The mechanism to lift the surface upwards proved to be increasingly challenging when scaling up. Doubling actuators by weaving them next to each other added sufficient force for lifting and forming localized openings. Though the surface may appear to have extreme curvature with exposed actuators, the surface appears as a continuous petal with less extreme curvature (Fig. 6, C-D).

F. Validation

We validated the full-scale prototype by comparing our 3D models (capturing the desired states) and the physical prototype for *Configurations-2, 3* and *4—Fully Actuated* (*most curved*), *Open to the Left*, and *Open to the Right*—that match the behaviors of the robot surface for the hotel lobby use case. To compare the 3D model with the constructed prototype, we compared key points of interest. To extract the depth data at various points of the physical configuration, we used a *Microsoft Kinect V2* [22-23] color and infrared depth (RGB-D) sensor, enabling the Kinect to capture depth and color images at the same time at frame rates of up to 30 fps [24]. Depth and color capture uses a marker-based system for point-to-point motion analysis. This produces accurate analysis; any minimal source of error was due to properties of the sensor, surface, and measurement setup [24-26].

Bright pink 3/4"x3/4" markers were placed on the surface

Figure 5. Actuator placement, *from left to right*, of the small, medium, and full-scale prototypes: solid color lines (actuators that are woven on top of surface), dashed lines (actuators woven underneath surface), red lines (actuators dedicated to curving the surface), blue lines (actuators lifting the surface), green lines (actuators curving and lifting the surface), and orange lines (actuators used for localized openings).

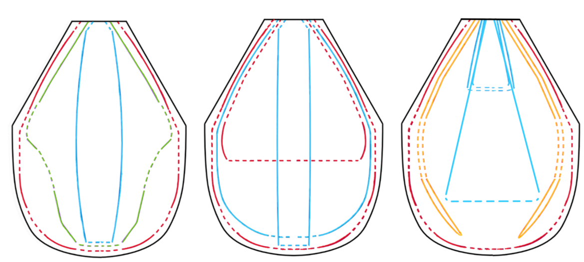
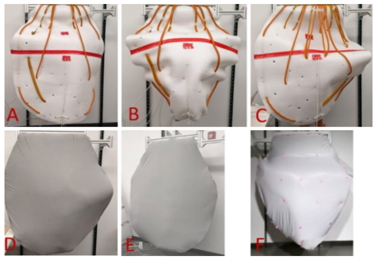


Figure 6. Full-scale prototype without (A-C) and with casing (D-F): A—actuator for left opening is actuated at 30 psi; B—actuator dedicated to curving actuated at 60 psi; C and D—actuator for right opening actuated at 60 psi; E—no actuators actuated; F—only actuators dedicated to curving and lifting are actuated at 60 psi.



at points of interest based on how the surface moved when the surface is actuated. A MATLAB program was used to capture the depth and color data as well as generate a point cloud with approximately 300,000 data points in a single frame. A MATLAB script was used to determine the range of RGB values for the markers, apply a mask to extract these points, determine the center of the region of interest that corresponds to each marker, and return the coordinates and plots of the markers. These tests were conducted in a dark room where high-intensity LED spotlights illuminated the surface.

To begin testing, a sample surface was developed following the procedure above. To permit full movement of the surface, the surface needed to be suspended at its intended height. To suspend the surface at the appropriate height, a fixture was created out of aluminum Bosch Rexroth channels. This fixture was then mounted to the wall at the required height. Pink squares were placed about the surface at twenty-three different locations where their locations would denote any change in surface structure between orientations. Once the appropriate actuators were inflated, the data acquisition methods described above were used to determine their locations. Using the 3D model created, a comparison could then be made between the orientations. This comparison took the form of comparing relative distances between points.

G. Results

To compare the 3D model and Kinect data, a metric was determined to quantify shape-changes in the surfaces: the distance between pairs of points on that surface. As the surface morphs, the distance between key pairs of points conveys how effective the robot surface changes shape to match what we expected for different useful configurations of the surface.

We chose 23 points by tracking where the surface experienced the greatest change in distance from deflating to inflating the actuators between configurations. On both the left and right sides, 10 points were needed to define each localized opening (tracing where the actuators were woven) and 3 additional points were added in the middle, towards the bottom, to track the midpoints of the 3 types of actuators: lifting, curving, and localized openings.

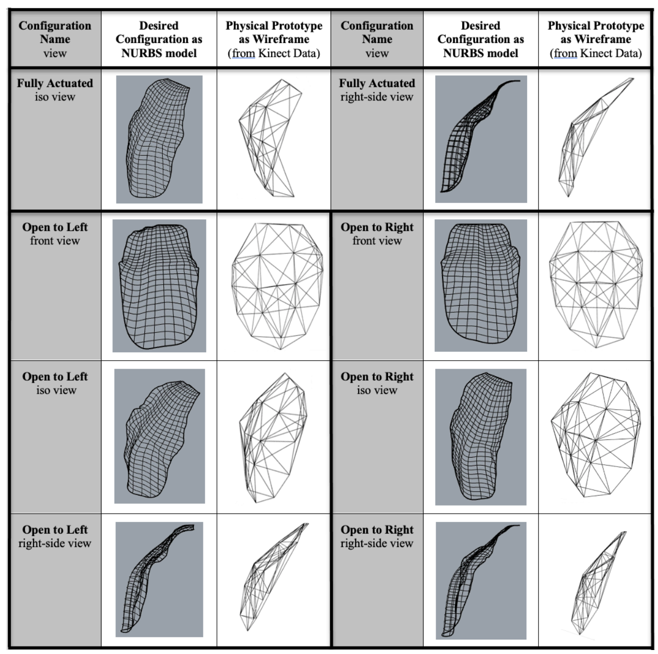
Using MATLAB, we created a wire frame (Fig. 7) from the marker locations captured by the Kinect for each of the three configurations as achieved by the physical prototype. Pairs of data points were compared by computing the L2 norm (Euclidean distance) for each pair of points. A threshold was then set to determine if points should be connected by a wire to contribute to the wire frame. Several different values were tried before a threshold that mimicked the true surface was found. This threshold was 2 feet.

After computing all the relative distances between points in both models, the distances themselves were compared using mean square error (MSE). The error calculated is for each point's distance to the marker in the upper left corner of the surface. The calculated errors for distance to this specific point are in the table below.

TABLE II. MEAN SQUARE EERROR VALUES (FT^2)

	NURBS Model Configurations	*Fully Actuated*	*Open to the Left*	*Open to the Right*
Prototype	*Fully Actuated*	.4026	.4585	.3401
	Open to the Left	.4898	.5673	.4284
	Open to the Right	.8288	.7847	.4930

Figure 7. Comparison of our Desired Configuration (as represented by a NURBS model) and the Physical Prototype (as represented by our wire-frame construction using 23 points captured by the Kinect sensor).



The small MSE values (Table II) and a visual comparison of the NURBS models and the wireframes generated by the Kinect capture of the physical prototype suggest that the woven McKibben muscle robot surface matched what we expected of our design for different useful configurations of the surface. Our results suggest that the configurations achieved by our robot surface under actuation can be predicted using the heuristic method described here—a predictability that suggests the utility of our approach for the design of robot surfaces by us and the research community in the future.

We made two discoveries when prototyping the full-scale surface. Firstly, we found that when weaving with two actuators instead of one, the resulting curvature of the surface was less than the instance of using one actuator. This is most likely due to the additional slippage that appears when two separate actuators are used. Secondly, we found that McKibben muscles have a limited capacity to actuate large structures. Once the surface grew to the scale of our full-scale prototype, the pneumatic actuators could no longer lift the surface from *Fully Actuated* (*Configuration-2,* most curved to the floor to make a space around the people meeting) to *Configuration-1* (most horizontal, to maintain views through the open-plan space). Moving from *Configurations 2* to *1* requires a scale-up in pneumatic actuators or a cable and pulley system actuated by motor. (We implemented the latter.)

IV. Conclusions and Future Work

We reported on robot surface research that was foundational and focused on a specific use case, validated quantitatively and qualitatively with a full-scale prototype. The foundational work involved developing and testing robot surface prototypes at three scales of different materials involving different patterns of weaving McKibben muscles with different substrates to create unique surface geometries including (for the first time, at large scale), a "spherical cap." We envision such robot surfaces mounted on or embedded in the walls and ceilings of rooms to support human activity. For the validation work, the locations of markers on the surface were captured using a Microsoft Kinect, and the locations of these data points were compared to a NURBS model for three configurations. Low MSE values and a close match, visually assessed between prototype and NURBS model suggest the utility of our method for the design of robot surfaces. (An example of a poor MSE would be 2.5 ft^2.) We found that the right-actuated model predicted each configuration better than the other models. Future work could benefit from higher fidelity modeling than possible by NURBs, such as analytical or finite element methods. Future directions include designing larger and smaller surfaces, developing woven surfaces with controllable stiffness, and testing and quantifying the effectiveness of different sized actuators at these larger scales. More broadly, the research reported here contributes foundational understanding of surface robotics.

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