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Design and Characterization of a Novel Robotic Surface for Application to Compressed Physical Environments *

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

I. Introduction

In robotics research and in industry, there are countless developments in robot arms. In contrast, robotic surfaces have seen less development and the work has primarily focused on interface devices with variations of continuous [1], discrete [2,3], and soft [4] surfaces. As we address later, there has been little exploration of robot surfaces, especially compliant ones, which morph to define habitable, physical spaces (physical environments) that give shape to the human activities within them.

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

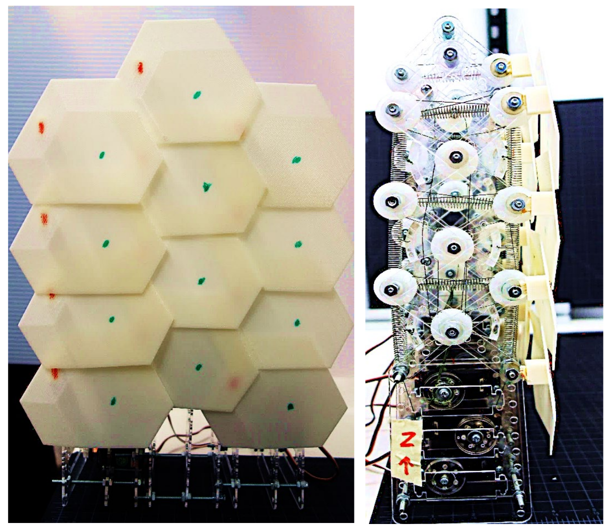

Figure 1. *CompResS*—a Compressed Robotic Surface (Front & Side).

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

We define a compressed pattern environment as comprised of malleable, adaptive, physical surfaces dependent on moving physical mass to arrive at shape-shifting, functional states supporting and augmenting human activities. In this paper, we

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present our prototype of such a surface: *CompResS*—a *Compressed Robotic Surface* (Fig. 1). As a self-supporting surface, *CompResS* is a robotic surface capable of morphing in two dimensions, affording the potential of creating habitable spaces that can be—theoretically at least—always different.

II. Previous Related Work

Before considering the design and characterization of our novel robotic surface, we briefly overview three prior, foundational efforts in this research domain, including one 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 [14], predating the *CompResS* prototype, and here presented for the first time.

Figure 2. (A*) HypoSurface*, (B) *MuscleBody*, and (C) *AWE.*

HypoSurface (MIT, 2003; Fig. 2.A) [15] is an interactive screen-wall that physically responds to sound, Internet feeds, and human gestures. *HypoSurface*, however, comes with a critical limitation: this dynamic surface is more a display of physical "pixels" actuated by a huge number of linear actuators of relatively short stroke that, overall, does not form space. *MuscleBody* (TU Delft, 2005; Fig. 2.B) [16] is a bulbous, McKibben-actuated, interactive volume that can accommodate several inhabitants who, by their actions, cause the transformation of its shape, transparency, and sound. The *MuscleBody*, however, cannot be precisely controlled. Our own *Animated Working Environment* or "AWE" (Fig. 2.C) [17] reconfigures itself to support specific human activities focused on collaborative work. AWE is distinguished by realizing more of the ambition of Mitchell's "robot for living in": it precisely configures an architectural space designed to purposefully support human activity (here, working life); however, it only reconfigures in one dimension. Our *CompResS* prototype overcomes these limitations, as will be made evident here.

III. System Description and Characterization

Our overall objective for *CompResS* was to design a reconfigurable, space-making surface applicable to the built environment with sufficient flexibility and control to achieve a multitude of room enclosures supporting wide-ranging human activity, and to meet the expectations of inhabitants. While an origami-inspired folding structure of hinged, rigid links (akin to our AWE [17] or Pop-Up Origami [18]) might achieve something of this objective, a smooth, compliant, continuum-like, robot surface was our preferred approach, given the soft and fluid motion of a continuum surface—qualities better matched to shaping the intimate physical surroundings of human inhabitants than would be a rigid, link-and-panel approach. Additionally, a continuum surface with its theoretically infinite degrees of freedom promises more formal "nimbleness" in creating a greater variety of physical room enclosures compared to an origami-like structure. The research team also has considerable experience in continuum robotics (our overview of this, [19]); nevertheless, the *CompResS* surface represents an approach not realized prior to this paper.

A. Theoretical Approach

In designing *CompResS*, we drew inspiration from nature, specifically in systems exhibiting behaviors we sought in a compressed robotic surface. We considered and experimented with a number of natural systems – among them, water waves, pineapple skins, and fish scales – to identify a promising model of inspiration. In prior work [20], we reported on our simulations of three such surfaces, inspired by three distinct natural systems, converging as a research team on one formal approach to the surface's design inspired by the pinecone. We converged on the pinecone approach following our evaluation of our animation studies of the three distinct surfaces.

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

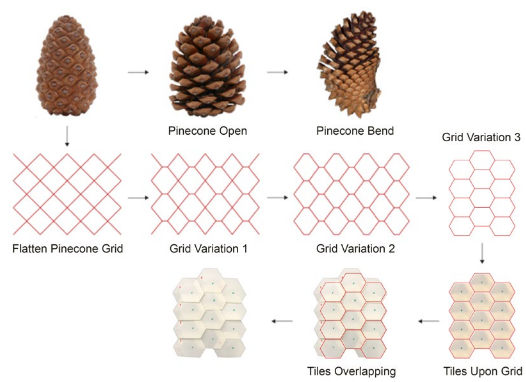

Figure 3. Iterative grid transformation resulting in the patterned scales of our Pinecone-inspired envelope.

B. Development of Continuous Grid Variations

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

Given the identified grid and aggregation units, we then modeled the units as an aggregated, “curved” surface divided by the grid. Our surface (Fig. 1) is designed to form an ample segment of a physical enclosure, with potential for application to the built environment. In our design process, we then proceeded to populate the units to create a surface as would be found in a natural pinecone. We then simulated the possible reconfiguration of “Open & Close” and “Bending” found in naturally occurring pinecones. In our simulations, transitions between reconfigurations proved to be very smooth, as previously reported [20]. Our subsequent challenge, reported here, was to design and evaluate a physical prototype capable of achieving physical configurations that were natural but also space-making and, so, capable of shaping human activity.

C. Prototype Design

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

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

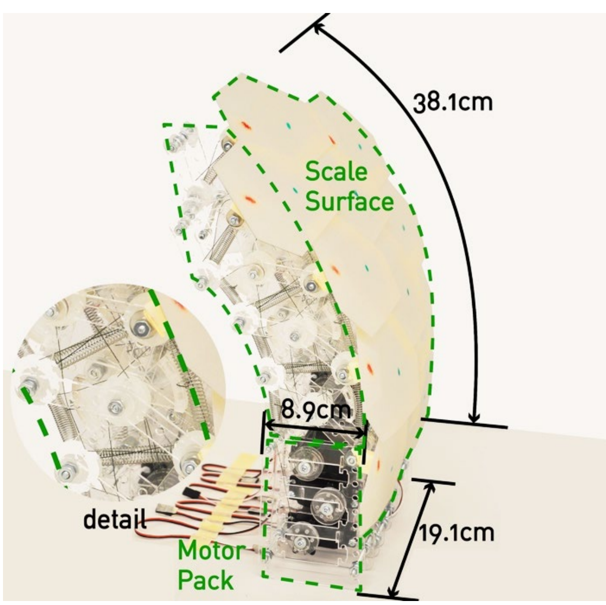

Figure 4. Section view of the built prototype.

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

D. Electrical Hardware Design

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

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

E. Structure and Surface Characterization

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

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

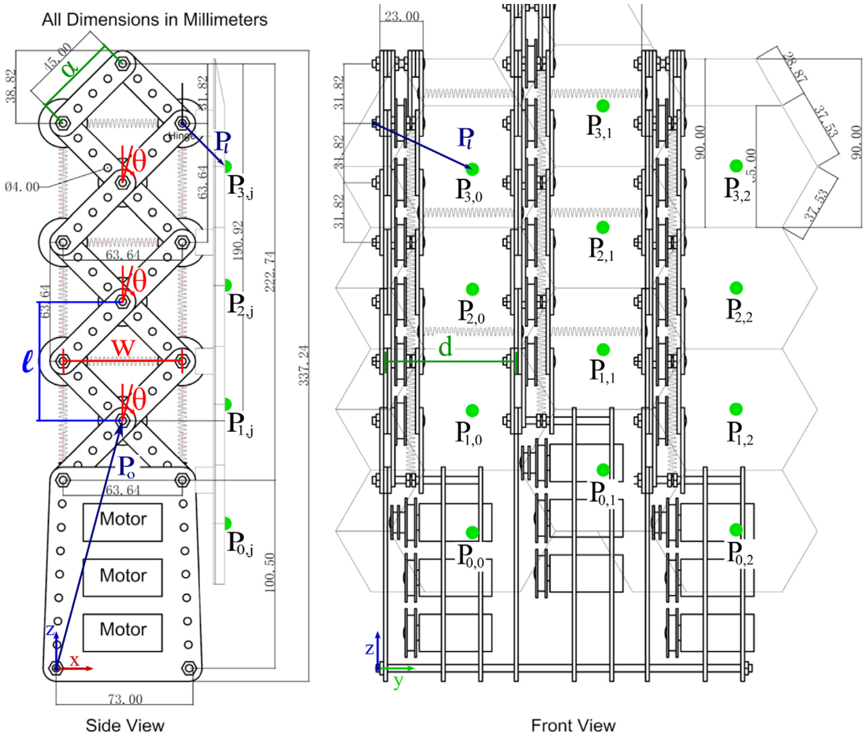

Figure 5. Section drawings of the prototype with all its dimensions and identification of three critical angles and length.

connections between the three trusses. This affords the very organic behavior of the continuous robotic system in the process of reconfiguring (as presented in our supporting video).

IV. Kinematic Model

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

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

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

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

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

The vector $P_{i,j} \in \mathbb{R}^{3\times1}$ describes the location of the *i*th discrete point along the *j*th truss on the surface. The matrix $R_{y,\theta_j} \in \mathbb{R}^{3\times3}$ is the standard rotation matrix around the y-axis by θ_j [21], measured with respect to the base frame. The scalar d represents the constant distance between two adjacent truss mechanisms along the *y*-axis and $P_l \in \mathbb{R}^{3\times1}$ describes the local offset of the measured points from the mounting point of the "pinecone" panels. The constant vector $P_o \in \mathbb{R}^{3\times1}$ is the offset relating the world coordinate system to the local coordinates of the surface. A visual representation of these values can be seen in Figures 5 and 6. The orientation of each discrete point, and the pitch of the panel corresponding to that point, can be described simply as $\theta_{i,j} = i * \theta_j$. There is no motion in the *y*-axis direction for any point along the surface, hence the *y* component of a surface point location is determined by the location of the related truss element (*j*) and the local offset P_l.

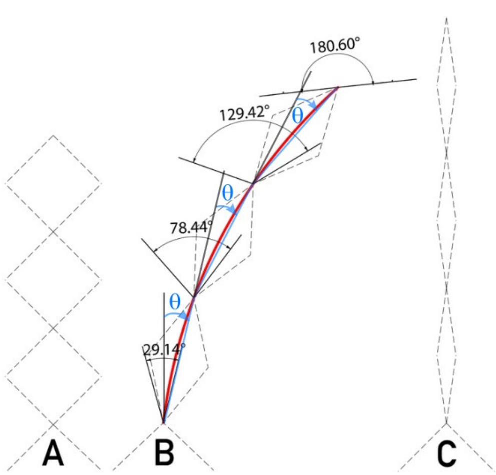

Figure 6. Range of motion, in section (A) fully-contracted and vertical; (B) bent and extended; (C) fully-extended and vertical.

V. EXPERIMENTS, IN SIMULATION, IN SHAPE MAKING

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

The four configurations were initially simulated as fixed (i.e. static) graphic images using parametric software (see Fig. 7—top row).

A. Simulation Model

Using the kinematic equations and the measurable constants of the physical system, a simulation model of *CompResS* was developed using MATLAB. As with the physical device shown in earlier Figures, the simulation shows the shape of each truss and the position and orientation of the interlocking plates of the robotic surface. An example of the model can be seen in Figure 8, where the left image shows the shape of *CompResS* and a series of discrete points in green, and the right image simulates the orientation and placement of the plates with the same series of discrete points. The simulation does not capture the physical interaction of the plates on the surface, so the simulated plates are not restrained from intersecting or overlapping. This simulation model was used to predict the location and shape of the *CompResS* surface for each of the proposed configurations.

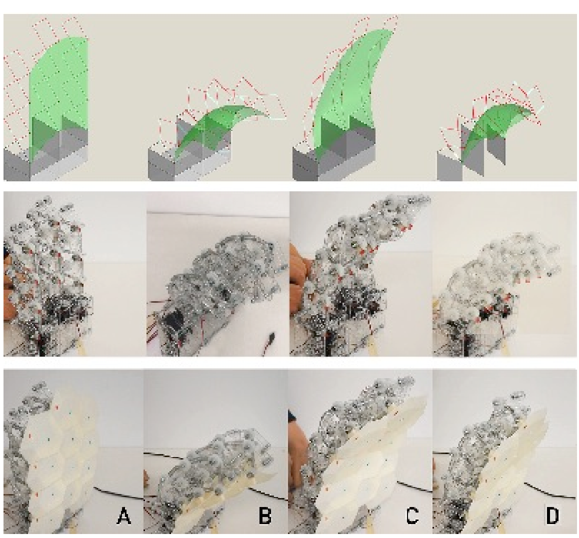

Figure 7. Experiments with shape-forming: 5 essential configurations (A) upright; (B) forward-bend; (C) forward-extend; (D) angled

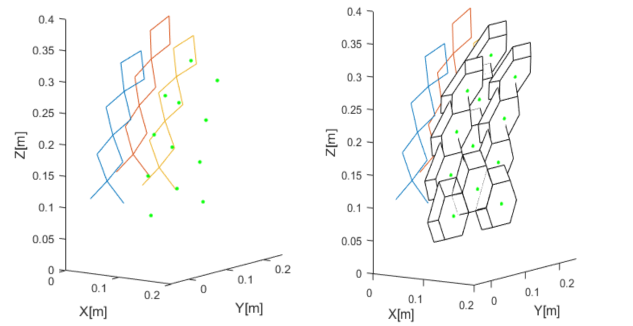

Figure 8. Simulation model of *CompResS.*

B. Experimental Design

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

C. Results

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

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

TABLE I. SUMMARY OF RESULTS

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

VI. Discussion and Future Work

A. 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 panels, in their current design, physically hinder one another and, thus, the trusses, so that the resulting surface geometry is distorted. In particular, (B) is not as precise as anticipated from the configurations assumed by the physical prototype without the surface panels mounted. This physical hindrance between the plates led to non-constant bending in each truss which caused increasing error along the length of each truss.

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

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

B. Future Work

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

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

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

Figure 9. *CompResS* used as acoustic panels and as a sculpted ceiling and wall canopy in a performance hall

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

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

VII. Potential Application

A potential application of the *CompResS* is for performance and concert spaces. As a wall and ceiling canopy, the panels could serve as acoustic panels, controlling the orientation of sound waves within the performance hall to enhance the audience's experience (Fig. 9). The panels could turn to orient towards the audience and could have some depth to decrease echo. If made of wood, the panels would also serve to resonate the tonal qualities of, for example, orchestral music which would offer the audience a sound experience similar to sitting within the orchestra during a performance. If the performance was being offered by a smaller, chamber group, the configuration could be easily altered to create a more intimate soundscape. Similarly, if the performance is one of a rock band, the panels could be used to dampen sound to control volume for the audience and draw out certain instruments. Additionally, these robot surfaces could be used outdoors to create a room-like space and a performance-hall sound quality. This is one of many applications for robot surfaces—a list of which was presented at the start of this paper. We welcome the challenge of developing a robotic surface at room-scale that is more capable of forming an enclosure that envelopes its inhabitants. *CompResS* is our initial step in achieving this objective.

VIII. Conclusion

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

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