A Research Through Design Exemplar of a "Compressed-Pattern Robotic Architecture" for the Information Age

Compression of patterns illuminates each of the patterns, sheds light on its meaning; and also illuminates our lives, as we understand a little more about the connections of our inner needs.

—Christopher Alexander, *A Pattern Language*, 1977

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INTRODUCTION

As familiar to many of us, A Pattern Language is Christopher Alexander's catalogue of the visual, spatial and tactile information embedded in architectural systems, and his argument for how this information shapes human behavior and, more broadly, the structure of architecture and society. Within this canonical treatise is a less obvious curiosity on which our paper and the investigation described here is constructed: Alexander's concept of "compressing" two or more patterns into a single space. To describe this concept of compressed patterns, Alexander offers a vision of translating the wide-ranging functions of a typical house into the confines of a single, ample room, resulting in a building that, in practical terms, exhibits (in Alexander's words) an "economy of space" that is potentially "cheaper" to realize. For Alexander, beyond flexibility, compactness, and potential cost savings, a compressed-pattern architectural work should also be fundamentally "poetic," offering in its compacted, patterned layers a "denser" meaning to its inhabitants. As Alexander maintained, "this compression of patterns illuminates each of the patterns, sheds light on its meaning; and also illuminates our lives, as we understand a little more about the connections of our inner needs."

We find suggestions of compressed-pattern architecture in the traditional house of Japan, in which inhabitants manually reconfigure shoji screens and tatami mats to create different spatial configurations within an open volume. Relatively more contemporaneous suggestions of a compressed-pattern architecture are found in the domestic environments designed and occupied by architects Gerrit Rietveld in Utrecht, Carlo Mollino in Turin, and very recently, by Gary Chang in Hong Kong. The latter, named the "Domestic Transformer," is a 330 square foot, single-room home of sliding walls and hinged panels manually reconfigured by its owner-architect to fashion any one of twenty-four different living patterns.

While these various suggestions of compressed-pattern architecture from across time and around the globe are compelling and informative, they all rely on manual reconfiguration—laborious and intrusive to the flow of everyday domestic activity, given the challenge and awkwardness of moving large and heavy physical masses with our own bodies, sometimes aided by simple machines. Emerging in recent years are accessible, less costly and relatively powerful means of reconfiguring the space of architecture through mechatronic and intelligent systems which have the promise to render architecture interactive and even intelligent, in real time, in ways Nicholas Negroponte and William Mitchell had envisioned—as "robots for living in" in the words of Mitchell.

In the last ten years, we have witnessed the early emergence of such an interactive and intelligent architecture, as presented at ACADIA as well as in the technical conference proceedings and journals of ACM and IEEE among other research media. Briefly, we consider three key examples of interactive and intelligent environments, both for their contributions and shortcomings, before presenting our own vision of a significant next-step in this trajectory.

HYPOSURFACE (DECOI/MIT, 2003)

HypoSurface is an interactive screen-wall that physically responds to sound, internet feeds, and human physical gestures. HypoSurface consists of an extensive fabric of small triangle panels controlled by linear actuators that collectively configure countless topographic surfaces (see video link in the bibliography). The flexibility of Hyposurface, however, comes with a critical limitation: this dynamic wall surface, capable of assuming countless configurations, is itself not designed in the way that might be expected of an architectural work: it is a non-descript wall of physical pixels, akin to a wall-scaled computer monitor with the added dimension of depth. Additionally, as a planar wall and not a volume, the HypoSurface does not form space in the conventional sense of architecture. While the HypoSurface represents a highly compelling new pathway at the intersection of Architecture and Computing, it falls short for us of realizing a robot for living in.

MUSCLEBODY (HYPERBODY RESEARCH GROUP, TU DELFT, 2005)

The MuscleBody is a playful, bulbous, interactive volume that can accommodate several inhabitants who, by their actions, cause the transformation of its shape, transparency and sound. Spatial reconfigurations of the MuscleBody are actuated by digitally-controlled, "soft" pneumatic muscles wrapping the flexible skin (see video link in the bibliography). Compared to the HypoSurface, the MuscleBody is more architectural with respect to forming and enclosing space, and having a discernable aesthetic quality. However, the MuscleBody has the shortcoming (shared with the HypoSurface) of not having an explicit architectural purpose for a target population of inhabitants. Despite its allure and accomplishment at the intersection of Architecture and Computing, the MuscleBody is more folly, more whimsy, than a purposeful, functional architectural work. Meanwhile, the MuscleBody is less precisely controllable compared to Hyposurface, so that the spatial patterns configured are not as purposeful as the patterns catalogued in Alexander's canonical book. In this respect, the MuscleBody is nearly but not fully yet a robot for living in. This critique by no means diminishes this and the subsequent, remarkable achievements of the Hyberbody Research Group, an oeuvre that substantially contributes to the emerging subfield of interactive and intelligent robotic environments that we recognize as engaging in a common pursuit.

THE ANIMATED WORKING ENVIRONMENT [AWE] (ARCHITECTURAL ROBOTICS LAB, CLEMSON UNIVERSITY, 2008)

The Animated Working Environment or AWE is an interactive and partly intelligent architectural environment that reconfigures itself precisely to support specific human activities focused on collaborative work, employing digital and physical tools and artifacts. Please see video link in the bibliography for AWE project details The total ensemble offers six preprogrammed configurations designed and tested to support a range of specific work activities. This ensemble can additionally be fine-tuned (and saved for later recall) by users via conveyed gestures presented to multiple IR sensors, which in turn signal the system to convey a given hinged connection towards or away from the user. Finally, the system has the basic intelligence to draw the hinged-panel assembly away from users in instances where users abruptly move in the path of the hinged panels. Compared to the HypoSurface and the MuscleBody, AWE is distinguished by realizing more of the ambition of a robot for living in: AWE precisely configures an architectural space designed to purposefully support human activity (working life), provides a level of control that can be recalled at a later time, and is characterized by (a small degree of) intelligence. However, it only reconfigures in one dimension.

Table 1 offers a comparison of these three key examples of interactive, robotic architecture and the features that might characterize our aspiration for a compressed-pattern architecture for the information age—a robot for living in. Our aspiration for CoPRA is to realize an architectural exemplar characterized as interactive, meticulously designed, precisely-controlled, spatial and spatially (2D) configurable, and purposeful in support of or augmenting the human activity of inhabitants.

	HypoSurface	MuscleBody	AWE	CoPRA
Interactive	•	•	•	•
Space Defining		•	•	•
“Architectural”		•	•	•
Purposeful function			•	•
Precisely Controlled	•		•	
2-D Configurable	•	•		•

Table 1: A comparison of three key examples of interactive, robotic architecture and our aspiration for CoPRA, a compressed-pattern architecture for the information age.

COPRA—A RESEARCH THROUGH DESIGN EXEMPLAR

We envision CoPRA as a design exemplar developed by us following from a Research through Design (RtD) methodological approach that may prove apt for a research community focused at the interface of Architecture and Computing. Introduced initially by Christopher Frayling in “Research in Art and Design” (1993), Research Through Design or RtD is a design research approach in which a modeled artifact is the outcome of a rigorous, design research process. The objective of RtD is to arrive at a designed artifact capable of “transforming the world from its current state to a preferred state.”

Within Computer Science, Research through Design has been employed increasingly in the research domain of Human Computer Interaction to such an extent that it has served to define a conference session at the most recent CHI conference, the gold-standard for HCI research. In elaborating the concept of RtD, Frayling defines four sub-approaches to RtD, the most apt for our investigation being “Development Work” and “Action Research.” “Development work” involves “using existed knowledge & technologies to do something no one had considered before, and then communicating results” with the utmost care and attention; while “Action research’ is “where a research diary tells, in a step-by-step way, of a practical experiment in the studios, and the resulting report aims to contextualize it … and to communicate the results.” At the core of RtD is a methodical, robust design process that is carefully scrutinized, recorded and reported. Our design research process and reporting has been faithful to this effort for rigor, reported in this account limited to so many words.

DESIGN REPORT

1.0 Logical Analysis to Clarify the Design Objective

Objective: To realize a flexible surface

Our overall objective is to design an interactive architectural space with enough flexibility and control to support human activity. Consequently, we need to design a physically reconfigurable, space-making surface, controlled with sufficient precision to respond to people's interactions and expectations.

Activity: Conceptualizing the design—three options for the flexible surface

There are three ways we approached the design of the flexible surface to achieve the expected behaviors of it. In Option 1, we employ flexible materials in the construction of the surface. In Option 2, small "scales" not dissimilar from the triangles of the HypoSurface are aggregated together to form the surface. In Option 3, we hybridize the approaches of the other two options to create numerous scales of different sizes and shapes that are both flexible and also controllable—a conceptual leap from the rigid triangles of the Hyposurface or the continuous flexible surface of the MuscleBody.

Analysis: Advantages and disadvantages of the two options

The challenge in Option 1 is how to precisely control the enveloping surface of CoPRA. Option 1 has the shortcoming of exhibiting limited design qualities in the surface geometry itself: how much control will we have in dragging control points or curves on the flexible-material surface over the behavior of the whole surface? In Option 2, control is precise but reliant on a fabric of triangular pixels and a very large number of actuators. In Option 3, we employ the advantages of the other two options while reducing the negative effects of their shortcomings: the pixels become flexible, fewer, and formed in a way that is designed already, without actuation, to organize a desired volumetric state. Given this, Option 3 has the best prospect to achieve the desired behavior of the surface as a whole characterized as flexible and precisely controllable. This hypothesis led us to our first design research experiment, which we named Tree Trunk (TT) following from its inspiration in the grain found in wood.

2.0: Conceptual model-1—Inspiration from Tree Trunk (TT)

Design Motivation: Viability of using a wood-grain pattern for the aggregation system

As we want CoPRA to provide space supporting specific human activities, a very high level of flexibility (as offered by HypoSurface) is unnecessary; what is required is the capacity of the system to achieve spatial configurations that can support likely users engaged in likely activities, with some "degree of freedom" factored in for the unexpected. It is understood that the geometry of CoPRA in any case defines and restricts the behavior of the whole aggregation system.

In designing CoPRA, we drew inspiration from nature, specifically in systems that have the kinds of behavior we expected in compressed-pattern architecture. We considered and experimented with a number of natural systems—water waves, pineapple skins, fish scales—to identify a promising model to draw inspiration from. A living tree, through its evolving grain and rings, served for us an apt model. The TT conceptual model was consequently inspired by the natural wood-grain patterning of trees. More than the other natural systems, wood-grain patterning demonstrates how two completely different patterns transform smoothly and continuously from one to the other. In brief, one geometric pattern permits certain behaviors to happen within the aggregate system; and two completely different geometric patterns allow two completely different sets of behaviors to happen within the aggregate system. This formal behavior of the living tree was judged to be a particularly productive model for CoPRA, given our expectation of its behaviors.

Activity 2.1: Digital prototyping the Tree Trunk

Two different patterns of wood-grain patterning found in nature were employed as the design inspiration for CoPRA: the “Circle Pattern” and the “Flowing Pattern.” The Circle Pattern geometry allows for extrusion within the aggregation system, while the Flowing Pattern geometry permits opening and closing of the aggregate system.

Evaluation: Animation Study of the Tree Trunk conceptual model

(Note: The animation studies of TT reconfigurations are accessible from https://vimeo.com/126005173, https://vimeo.com/126005172 and https://vimeo.com/126005171)

Our animation study “TT Rigid Strip Open & Close” (https://vimeo.com/126005171) shows the reconfiguration of a system of 24 striations made by the wood grain patterning, forming the surface envelope (see the animation study video). The study reveals that the reconfiguration of the CoPRA model doesn’t run very smoothly: clearly discernable are collisions (intersections) occurring between striations, even when the opening is relatively modest. If the model contains, say, 48 striations, this kind of collision might be avoidable.

Analysis: Problems discerned through the animation study, and speculation on possible solutions

The collision recognized in our animation study clearly provides critical information: that the reconfiguration of the surface is strongly impacted by the geometry of each physical striation. To be successful, at least formally, the striations of our model would need to be redesigned to avoid collision. Alternatively, the striations could be made from flexible materials, as shown in our “Soft Material Strategy” within our same animation study (https://vimeo.com/126005172).

The reconfiguration permitted by the Circle Pattern presented as part of our animation study, “TT Extrusion,” is smooth and therefore judged fruitful. While the Circle Pattern reconfiguration is relatively simple and limited to localized control, it has great impact on the surface curvature of the aggregate CoPRA system. Nevertheless, the Circle Patter and the overall TT model were found inadequate for achieving the desired behaviors.

3.0: Conceptual Model-2—Inspiration from Pine Cone

Design Motivation: Viability of using a pine cone structure for the aggregation system

As the TT model was judged inadequate for achieving the desired behaviors, based on our animation study, we developed a model inspired by the pine cone, an organ on plants within the division, Pinophyta (conifers). The pine cone is a particularly apt inspiration for CoPRA for its two formal attributes: (1) the pine cone aggregation is 3-dimentional and spatial, comprised of similarly shaped and sized but not all identical units (scales); and (2) the pine cone is not static but instead undergoes many cycles of opening and closing during its life span (see Figure 1). More pertinent to our expectations of CoPRA, the pine cone naturally performs the “Open & Close” and “Bend” behaviors, even if these reconfigurations are happening over a very long time span (several months, even a year) and under certain conditions are irreversible. As a model drawn from nature, the pine cone lends CoPRA the prospect of spatial continuity instead of surface continuity. Here the ‘spatial continuity’ means even though each scale (or unit) is moving away from each other during the reconfiguration process (bending), people still perceive the aggregation as a continuous surface as the 3-dimentional units are connecting with each other spatially (Animation https://vimeo.com/126004689 shows the idea of ‘spatial continuity’).

Activity 3.1: Concept development of continuous grid variations

With the pine cone as our starting point, we begin to analyze the key geometric characteristics of this living object—the logic of translating a promising biological inspiration into a design model (Figure 1). The formal focus of this design development process is the grid. The grid of the aggregation determines how many types of units (or scales) will comprise the system, and the relationship across adjacent units. Undoubtedly, different grids generate different units and overall aggregation systems; however, as represented in figure 1, the different grids shown represent different states of a continuous grid in the process of transforming (reconfiguring). There are three possible approaches to develop the dynamic behavior of CoPRA drawing inspiration from the pine cone behavior: (1) we can identify a certain state of this continuous grid transformation as our grid that generates our design system, or (2) we can identify two different states of the continuous grid transformation to generate two different components of our design system, integrated together to form one composite grid, or, (3) we can identify many states integrated together to form one composite grid, with the difference between each state being small enough to be seen as continuous (i.e. smooth, natural). While options (2) and (3) are in concept more compelling than (1), we choose for this investigation option 1, where one state of the continuously transforming grid (in Figure 1, the second state from the left) as the grid that generates our design system. As shown in Figure 1, the identified state is the starting point for detailed design development of the aggregation of units (i.e. pine cone scales). This design process, which we define as a construction principle, is applicable to any state of the continuous grid transformation, meaning that any state can generate an aggregation unit employing this same construction method.

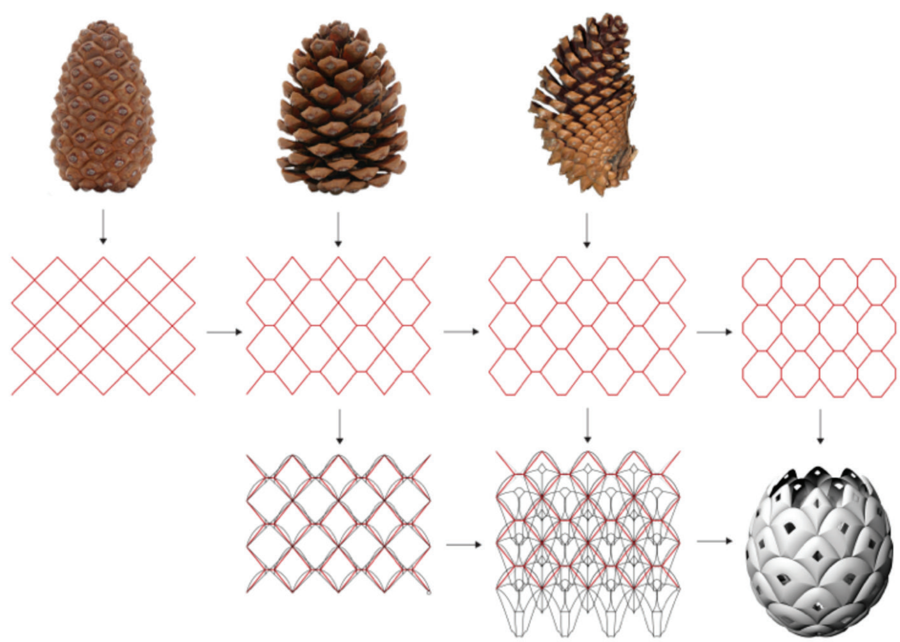

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Figure 1: Pine Cone Concept Continuous Grid Transformation, *TOP: Natural movement of the pine cone, opening and bending. CENTER: Pine cone grid transformation (potentially continuous).BOTTOM: Iterative grid transformation resulting in the patterned scales of our Pine Cone Model.*

Activity 3.2: Digital prototyping the Pine Cone Model

Given the identified grid and aggregation units, we then modeled the units as an aggregated curved surface divided by the grid. This surface defines a space (volume), with potential for architectural applications. In our design process, we proceeded to populate the units onto the surface as would be found in a natural pine cone to achieve our architectural-robotic Pine Cone Model (Figure 1 bottom-right).

Evaluation: Animation Study of the Pine Cone model

(Note: This animation studies of Pine Cone reconfigurations are accessible from https://vimeo.com/126004694 and https://vimeo.com/126004695)

We simulated the possible reconfiguration of “Open & Close” and “Bending” (Figure 1 and the Animation—Pine Cone Open and Close https://vimeo.com/126004695, Animation—Pine Cone Bending https://vimeo.com/126004694). The reconfigurations proved to be very smooth.

Activity 3.3: The Design of CoPRA-1, an architectural robotic system following our Pine Cone Model

Are subsequent challenge was to design the mechanism of a robotic pine cone that was capable of realizing the reconfigurations defined by the behaviors, “Open & Close” and “Bending.” Our mechanism (Figure 2 and Figure 3) allows the whole system to bend by spring, controlled by servo motors winding tendons attached to the horizontal columns. This mechanism also allows for rotation by a “spring and stick” system (Figure 3): the stick pulls the tendon connected to the servo motor. By changing the scale of this pine cone-inspired artifact, we envision this concept to be applicable to wide-ranging architectural conditions, from furniture to skyscrapers (see Figure 5).

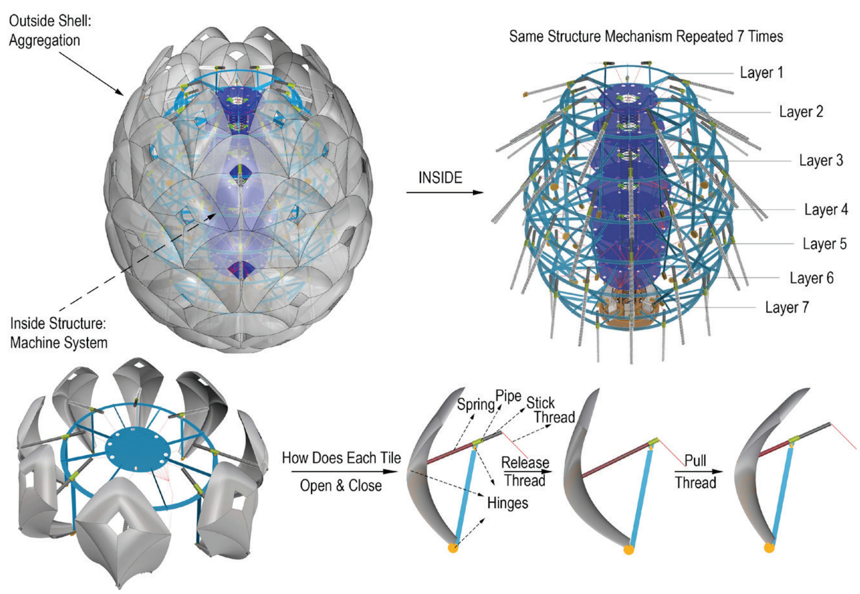

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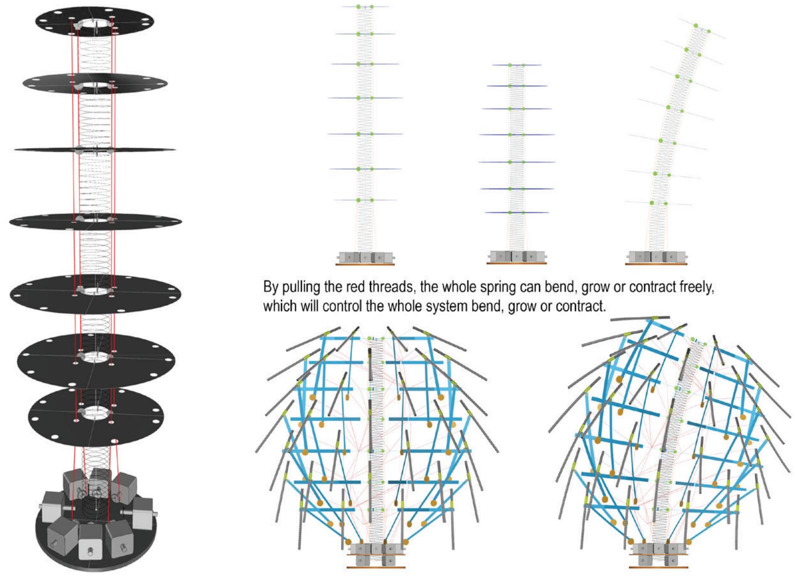
Figure 2: CoPRA-1, Pine Cone Model—seven actuated layers organized on the vertical axis

Activity 3.4: The Design of CoPRA-2, a robotic system following our Inverse Pine Cone Model

CoPRA-1 (Pine Cone Model) is apt for an architectural application (e.g. a building or furniture artifact) which foregrounds the exterior, given that the articulating structure is located within the artifact such that, what is visible from the outside is an elegant, continuous form comprised of scales (like that of the pine cone or the static but similarly inspired Gherkin building in London, by Foster + Partners). If, alternatively, the interior of the volume should exhibit the same elegant, continuous form comprised of scales, such as for a modest room-scaled space, then the robotic structure must be moved to the outside of the envelope. To achieve this condition, we investigated inverting the relationship of structure and envelope found in CoPRA-1 to create CoPRA-2, which represents an Inverse Pine Cone Model (Figure 4). The Inverse Pine Cone Model is essentially comprised of the “Stick & Spring” system employed to realize the “Open & Close” reconfiguration considered earlier (Figure 3); the only difference



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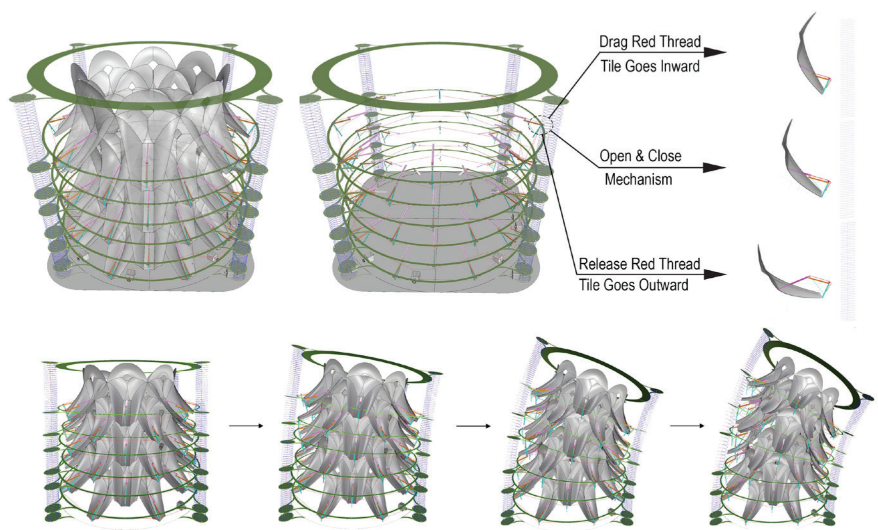

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Figure 3. CoPRA-1, Pine Cone Model—vertical structure and bending behavior, *structural design of the vertical axis, and diagrams of its Contracting and Bending behaviors.*

Figure 4. CoPRA-2, Inverted Pine Cone Model—structural design and bending behaviors. *The Inverted Pine Cone Model serves well as an interior space where inhabitants experience a continuous envelope of pine cone scales; the mechanics are meanwhile hidden outside the occupied space.*

is that we now have four springs external to the envelope located at four corners of what is essentially a square or rectangular plan, which realize the bending reconfiguration. (In CoPRA-1, the Pine Cone Model, we only employed one spring to achieve the same behavior.) In this way, the Inverted Pine Cone (CoPRA-2) evacuates the robotic structure from the interior, inhabitable space, allowing freely for its occupation by inhabitants.

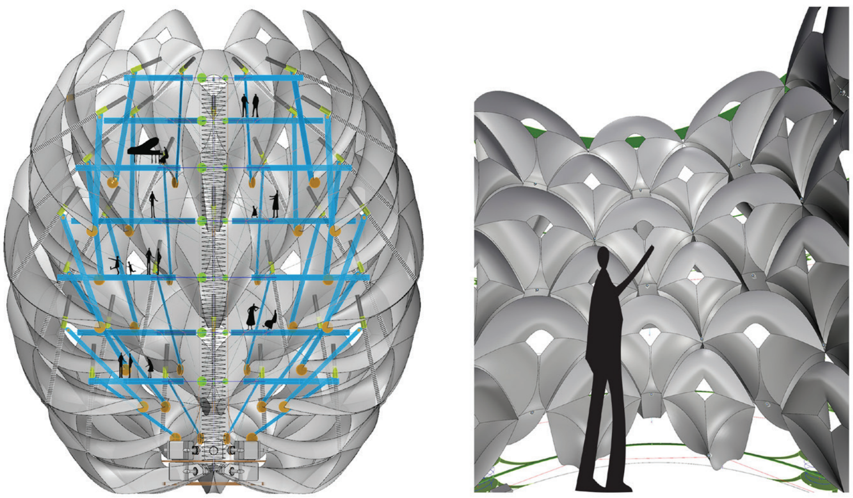
Evaluation: Animation Study of Inverted Pine Cone to simulate possible configurations

(Note: This animation study of Inverted Pine Cone reconfigurations are accessible from https://vimeo.com/147739066, https://vimeo.com/126004689 and https://vimeo.com/126004690)

Our Animation Study of the Inverted Pine Cone offers insights as to possible problems with the system when it performs "Bending" reconfigurations. (Animation: https://vimeo.com/147739066) The same Animation Study provides some sense of the experience of the model interior during these reconfigurations. (Figure 5 and Animation: https://vimeo.com/126004689) We learn from this Study that the Inverted Pine Cone exhibits a smooth reconfiguration. Consequently, we see merit in both CoPRA-1 and CoPRA-2 applied as a conceptual model for wide-ranging architectural applications.

CONCLUSION

In this paper, we have classified the Pine Cone and Inverted Pine Cone as two conceptual models of Compressed Pattern Robotic Architecture (CoPRA). A CoPRA is an architectural exemplar characterized as interactive, meticulously designed, precisely-controlled, and spatial and spatially (2D) configurable that aims to be purposeful in support of, or augmenting the human activity of inhabitants. By means of a Research through Design process (reported briefly in the limited space here), we judged the two conceptual models, CoPRA-1 and 2, to



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have the potential to be architecturally meaningful, as they physically changed the shape of the envelope—smoothly, naturally, organically—by way of two distinct but coupled behaviors ("Bending" and "Open & Close"). These reconfiguration processes are both simple and organic, which we believe make them realizable and beautiful.

More broadly, we view CoPRA as a design exemplar defined by Research through Design. CoPRA, in this light, is not unlike the Dom-ino of Le Corbusier: a classification of a built environment artifact at the intersection of Architecture and Engineering. Like the Dom-in, CoPRA accommodates different architectural patterns in one physical space; but unlike Dom-in, accomplishes this flexibility through reconfigurations achieved by robotics. Obviously, scaling the Model for real architectural applications in the built environment will require extensive technical study to satisfy structural and safety demands, and these demands suggest that our Model is, in the short term, with modest resources, achievable as an interior envelope within an existing building more than serving as a building itself. As such, we envision the prospect of wide-ranging architectural applications for CoPRA as an interior-shaping concept. For instance, CoPRA can serve as the concept for a reading or conference room that reconfigures continuously and automatically to achieve the best daylighting of the space at a given instance during the course of a day. Moreover, CoPRA might serve as a concept for emergency relief efforts as a compact mobile hospital or perhaps a space for strategic planning in extreme conditions. Alternatively, CoPRA might form the envelope for a library unit delivered to the interiors of existing, branch public libraries serving underserved communities, the likes of which would otherwise not receive library facilities exhibiting much in the way of functional, technological or design sophistication.

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Figure 5. Potential architectural applications of CoPRA at two physical scales.*LEFT: A section through the Pine Cone Model applied to a hi-rise building.RIGHT: An interior view of Inverted Pine Cone Model applied to a room interior.*

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Comprised of team members representing architecture, electrical & computer engineering, and library & information science, our interdisciplinary research team, is in fact developing such a library unit in cooperation with and for a library system in a poor rural county. We envision the compressed patterns of this library, achieved through the CoPRA concept, to afford local library users the capacity to meet, collaborate, and make, present, and display digital and physical things they imagine in the confines of a compact volume. Our future work with CoPRA, consequently, involves the application of this Model as a full-scale, fully functioning library unit, iteratively designed, prototyped and evaluated in situ with participation from the librarians and likely patrons of the underserved community—our design partners.