CoPRA—a Design Exemplar for Habitable, Cyber-physical Environment

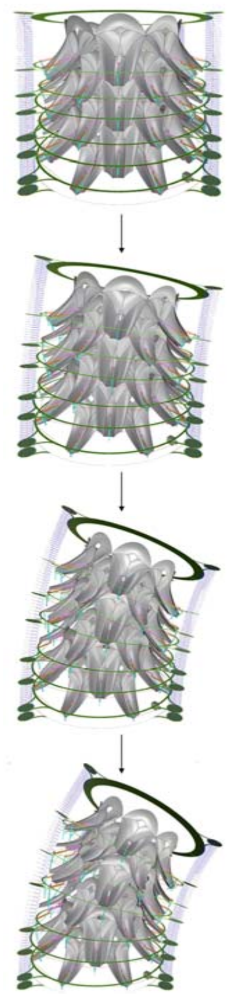

Figure 1: Bending movement of CoPRA design exemplar

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Abstract

This paper introduces the concept of “Compressed-Pattern, Robotic Architecture” (CoPRA) a *design exemplar* for purposeful, inhabitable, intelligent physical environments, spatially reconfigured by means of robotics. CoPRA is inspired by Christopher Alexander’s notion of a “Compressed-Pattern Architecture,” in which a single living space is reorganized to become many different, functional rooms. In our exemplar, however, this reorganization is not performed by inhabitants manually, but instead by robotics actuated in response to human activity. CoPRA represents a productive conceptual model for a growing research community within CHI focused at the interface of architectural design and embedded systems.

Keywords

Design theory; cyber-physical systems; robotics; interaction design.

ACM Classification Keywords

B.5.2 Design Aids—Simulation;
D.2.2 Design Tools and Techniques—User interfaces;
H.5.2 [Information Systems]: User Interfaces—*Theory and methods;* H.1.2 User/Machine Systems—*Human factors.*

Figure 2: HypoSurface

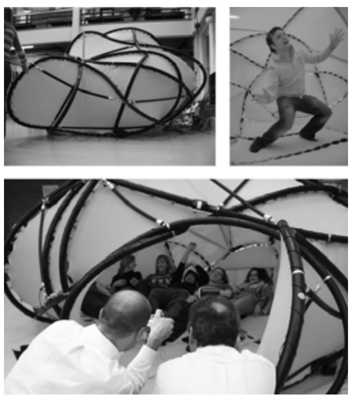

Figure 3: MuscleBody

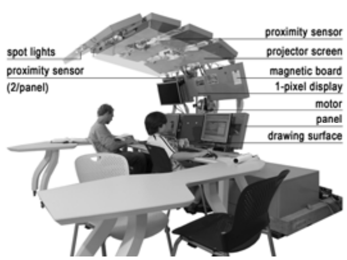

Figure 4: The Animated Working Environment [AWE]

Introduction

"A Pattern Language" [1] is Christopher Alexander's catalogue of the visual, spatial and tactile information embedded in the built environment, and his argument for how this information shapes human behavior. Within a pattern language 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 an "economy of space" that is potentially "cheaper" to realize. For Alexander, a compressed-pattern environment 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" [1].

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 [2].

However, these existed compressed pattern living environments all rely on human memory and labors for space reconfigurations. Emerging in recent years are accessible, less costly and relatively powerful means of reconfiguring the space of the built environment through mechatronic and intelligent systems which have the promise to render physical environment 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 built environments, Briefly, we consider for the broader CHI community 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 (see video link in the bibliography & Figure 2) [3]. The flexibility of Hyposurface, however, comes with a critical limitation: this dynamic wall surface is itself not designed in the way that might be expected of an architectural work. Additionally, the HypoSurface does not form space in the conventional sense of architecture.

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 (see Figure 3) [7]. However,

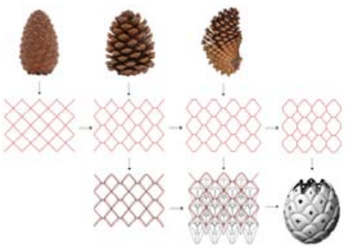

Figure 2: Pine cone concept continuous grid transformation.

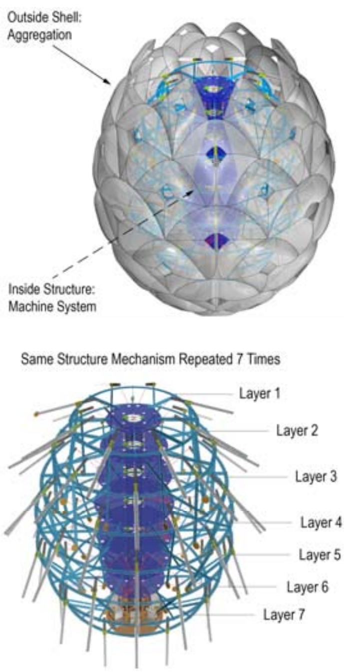

Figure 3: CoPRA-1, Pine Cone Model—seven actuated layers.

the MuscleBody has the shortcoming (shared with the HypoSurface) of not having an explicit architectural purpose for a target population of inhabitants. Meanwhile, the MuscleBody is less precisely controllable compared to Hyposurface.

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 [6]. Please see video link in the reference & Figure 4 for AWE project details. AWE is distinguished by realizing more of the ambition of a robot for living in: it precisely configures an architectural space designed to purposefully support human activity (working life), 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.

Qualities	HypoSrf	M-Body	AWE	CoPRA
Interactive	●	●	●	●
Define Space		●	●	●
Architectural		●	●	●
Purposeful function			●	●
Precisely Controlled	●		●	●
2-D Configurable	●	●		●

Table 1: Comparisons of Examples and CoPRA

CoPRA– a Research through Design Exemplar

We envision CoPRA as a design exemplar developed by us following a Research Through Design methodological approach [4], [5], [8], [9]. Introduced initially by Christopher Frayling in "Research in Art and Design" (1993), Research Thzrough Design or RTD is a design research approach in which a modeled artifact is the outcome of a rigorous, design research process.

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" [4]. At the core of RTD is a methodical, robust design process that is carefully scrutinized, recorded and reported. In our design research we aspire to the same communicated as follows in the form of a "research diary".

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

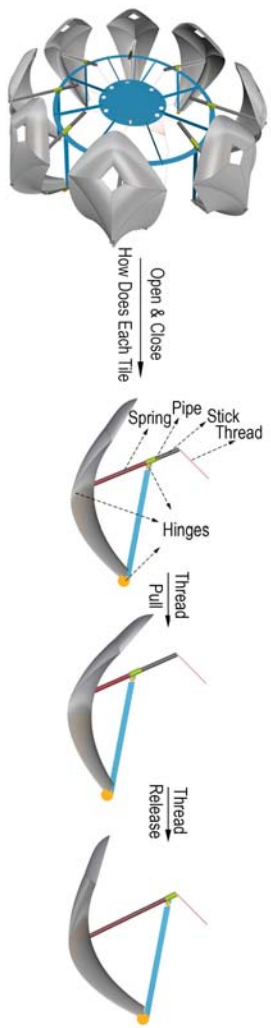

Figure 4: The mechanism of "open and close" system.

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 design research experiment shown below.

2.0: Conceptual Model– Inspiration from Pine Cone

Design Motivation: Viability of using a pine cone structure for the aggregation system
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 2). 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) 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 2.1: 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

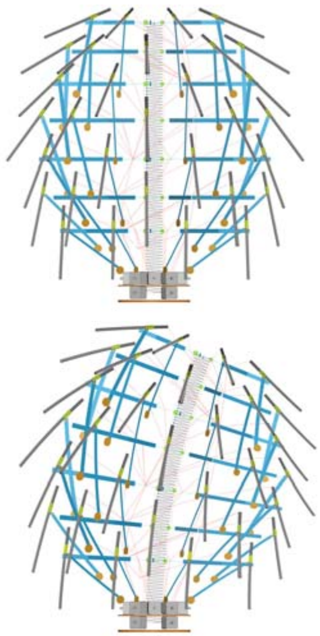

Figure 5: Bending movement.

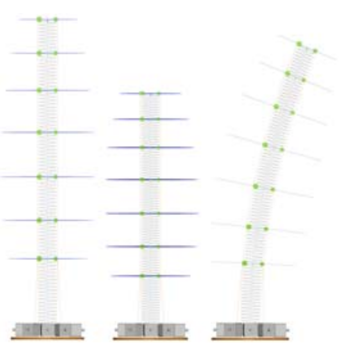

Figure 6: “Tendons & Spring” spine system

inspiration into a design model (Figure 2). 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 2, the different grids shown represent different states of a continuous grid in the process of transforming (reconfiguring). As is shown in Figure 2, we choose one state of the continuously transforming grid (in Figure 2, the second state from the left) as the grid that generates our design system. We can see in Figure 2 that 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.

Activity 2.2: 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 2 bottom—right).

Evaluation: Animation Study of the Pine Cone model
We simulated the possible reconfiguration of “Open & Close” and “Bending” (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 2.3: 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 3, Figure 4, Figure 5 & Figure 6) 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 4): the stick pulls the tendon connected to the servo motor.

Activity 2.4: 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 7 & Figure 1). The Inverse Pine Cone Model is essentially comprised of the “Stick & Spring” system employed to realize the “Open & Close” reconfiguration

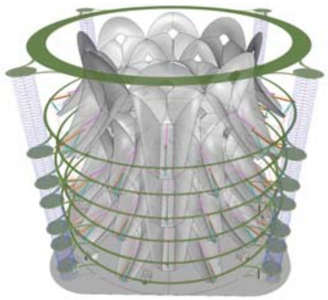

Figure 7: Inverted pinecone structure detail.

Figure 8: “Library Cube” in working hours.

Figure 9: “Library Cube” in non-working time.

considered earlier (Figure 4); the only difference 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.

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. (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 such as the interior robotic canopy in Figure 8 & Figure 9.

Implications for the CHI Community

We view CoPRA as a design exemplar of a large-sealed inhabitable cyber physical system, or alternatively, a physical architectural environment for the information age, developed there through a RTD process. 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. Finally, CoPRA has potential for application to the autonomous car interior and to space habitats. For the CHI Community, CoPRA opens a possible new frontier of exploration at the scale of habitation.

Recommendations for Further Investigation and Incorporation into Practice

Comprised of team members representing architecture, electrical & computer engineering, and library & information science, our interdisciplinary research team, our future work with CoPRA, involves the application of this Model as a full-scale, fully functioning library unit—Library Cube (Figure 8 & 9), iteratively designed, prototyped and evaluated in situ with participation from the librarians and likely patrons of the underserved community—our design partners.

Acknowledgements

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