1 Introduction

"Like medicine, it (architectures) must move from the curative to the preventive."

Cedric Price

§ 1.0 Structural Introduction

This research examines three fundamental topics: Computation, Embodiment, and Biology to develop a design framework for developing Organic, Interactive Architectures. The design framework is termed "HyperCell", which involves, developing real-time interactive designs leading to novel organic architectural proposals. Furthermore, such a biotic space advances the next level of artistic and philosophical discourse via broadening the range of innovative interactive architectural design thinking. The ultimate goal of the research is to evoke and enrich more innovative interactive architectural design to take place in the near future.

§ 1.1 Background and Problem Statement

Digital, Organic, and Interactive Architecture.

The semantic and semiotic sense of "**Digital**", "**Organic**", and "**Interactive**" architecture is explored. "**Digital**" refers to designs using digital design and fabrication technologies including parametric design, generative computation, digital form finding etc. "**Organic Architecture**", apart from the original definition coined by Frank Lloyd Wright, now

incorporates overtly complex appearances of architectural space produced using contemporary computational techniques. "**Interactive Architecture**", is usually perceived as a building covered with either a delicate mechanical façade which adapts to its surrounding environment or a media skin in the form of an information vehicle.

Digital Architecture is undoubtedly associated with "**Computation**". By perceiving the evolutionary process of CAAD (Computer Aided Architecture Design), it is quite impressive to note how architecture took advantage of computational technologies in various aspects: from data storage, spatial modeling, rendering based representation, and animation, to the current design trends of parametric design and digital fabrication. Computation is omnipresent in contemporary architectural design practice from the initial conceptual design phase to the end production process. Nevertheless, computer usage is largely dedicated to redraw and store technical drawings. This makes one wonder whether computational technology has been properly implemented in current architecture design. Is it possible to shift the mind-set of designers from developing "**Computer Aided Architecture Designs**" to a mindset promoting "**Computation embedded within Architecture**"? This will imply empowering the entire space with computational intelligence, thus allowing it to interact not only with the surrounding environment but also with the users inside the space and with the building components formulating the architecture itself. As a second evolution in this change of mindset, is it possible to create a biological cell-like intelligent architectural building block with embedded computation, which can sense, react, communicate, and even interact, in order to compose a holistic intelligent architectural body?

The same issue applies to **Organic Architecture**, especially in today's context, when young architects are mostly fascinated with computational assistance for Form Generation. As mentioned before, **Organic Architecture** at present is mostly a term used for describing formal architectural qualities akin to organic curvilinear shapes by taking advantage of computational techniques of parametric and algorithmic design. Multiple algorithms for generating such so-called organic shapes are freely available and easily assessable to young architects to apply to their architectural designs. Unfortunately, this approach of focusing on mimicking organic shapes without understanding their biological significance seems to be an inevitable wave rapidly spreading out in today's digital architectural context. Computational technology is thus disembodied and reduced to a mere generative tool for churning out strange organic shapes, while it could be deployed to embody an intelligent environment. The other critical issue is that even when such forms of architecture are ingenuously generated by the application of complex algorithms, almost all of such so-called **Organic Architectures** end up with a static optimized character which is totally contrary to how the organic world factually operates: in a dynamic fashion. Every living/organic entity is constantly changing/evolving (at variable scales: atomic, cellular) whether rapidly or gradually

at its own pace and is naturally condition to follow the flux of the environment within which it is embedded. This primary quality of the organic world should be echoed in any architectural, entity which claims to be **Organic**. This implies not crystallizing architecture into static expressions of flowy forms, but rather the embodying the ability to process contextual information flow like a natural organic body.

Apart from developing such organic-appearance-oriented design, some architects have dedicated themselves to seriously investigating bio-inspired principles in their architectural designs via material studies, understanding structural/energy flow logics or via advanced bio-digital fabrication (e.g., Neri Oxman in Arts and Sciences at the MIT Media Lab, and Achim Menges of Institute for Computational Design at the University of Stuttgart). However, still, a crucial character in nature, which is constantly forgotten, is "**Integration**". Nature is mostly multi-performative, unlike artificial mono-performative architectural systems. In nature, to build up organic bodies, the material is applied as supporting structures as well as the transporting paths for water and nutrition through a self-assembly approach. It thus integrates multiple functions for enhancing efficiency and intelligence of the organic body. This is why the organic body is so mysterious, admirable and worth studying and learning from. But to be aware of this is not the ultimate goal of the research. Rather, creating a novel living, constantly data processing architectural species, embedded in the principles of natural morphogenesis, as a refined interactive architecture becomes the ultimate goal of the research.

Examining the current development of Interactive Architecture, it becomes apparent that most projects remain at the level of façade design adapting to the external environment instead of having tangible impacts on the users inside the space (e.g., Arab World Institute in Paris designed by Jean Nouvel, and Al Bahr Towers in Abu Dhabi designed by Aedas). The research suggests a change in this prevailing scenario and provides a direction involving real-time user-space interactions from a user-centric perspective. In this case, both the human body and the architectural space become crucial communication mediums. **The ultimate goal of the research is thus to create buildings as embodied organic bodies which can interact with the external environment, the users inside as well as amongst their constituting building components.** When it comes to the discussion of The Architectural "**Body**", it certainly implies the embedding of computational technologies concerning real-time sensing, actuation, communication & control protocols. To achieve true "**Integration**", one must strive to achieve synergy between **Digital/Computational Architecture**, **Organic Architecture**, and **Interactive Architecture**. The questions of how to conceive and design such an integrated, intelligent, and interactive architecture shall be answered in the explorative journey of this research which will cover the domains of **Computation, Embodiment, and Biology (Organic).**

§ 1.2 Research Questions

The main research question addressed in this research involves issues pertaining to a synergistic combination of the three major domains of: "**Computation**", "**Embodiment**", and "**Biology**". Several sub-questions subsequently emerge from this main research question and these are elaborated in accordance to these individual associated domains:

Is it possible to develop a rule-based design framework for creating interactive architecture for the generation of novel authentic organic architecture which aptly utilizes computation capabilities to generate an intelligent, body-like, and tactile interactive environment following the principles of morphogenesis derived from natural organisms?

In order to answer this main question, several related sub-questions are explicitly outlined:

Computation (Chapter 3):

How have computational technologies and their applications in architectural design evolved?

It is crucial to have an overall picture of the evolution of computational technologies and their application in architectural design to predict future trends and propose novel directions to ensure the apt usage of computational technologies. Computation techniques have been harnessed in architecture in various capacities, ranging from data storage, renderings as representation purposes, 3-dimensional modeling, to develop parametric models with relational logics etc. to name a few. But most of the time these technologies are used for form-generation purposes, which limits its potential applications in architectural design. The research would like to propose a novel approach for utilizing computational technologies for developing embedded intelligence within architectural components (smart building blocks) which populate a built form. Communication protocols between such components to enable collective intelligence based decision making can thus become a vital feature of such architectural bodies in a bottom up fashion.

With the assistance of computational techniques, what will be the new role/definition of "FORM" in the context of this research?

Computers essentially were meant to be invented as calculating machines dealing with numbers and data sets. After the emergence of computation as a plausible assistant to architects, it became possible to sculpt various non-standard forms could be by using 3D modeling software. In this context, "**Form**" has been treated as a generative outcome of a computation process in the form of an architectural object with a certain expressive appearance. However, this research proposes to interpret "**Form**" in a different manner, as an information processor in accordance with the preferable computational methodologies the designers choose. Along with the evolution of the computational technology and their implementation in architecture design, this research also defines Form as a ***Form Sculptor, Form Generator***, ***Form Animator***, and ***Form Interactor*** in accordance with the means with which the designer generates and defines their architectural **Forms**. Ultimately, it intentionally implies that the development of computational technology in architectural design should shift more towards providing for Interactivity in Architectural Form via dynamic engagement with the natural and artificial environment.

Embodiment (Chapter 4):

What is the connection between architectural space and embodiment from a theoretical or conceptual point of view?

Expanding upon Marshall McLuhan's "***Body Extension***" notion (McLuhan, Understanding Media: The Extensions of Man, 1964), Architecture or rather the built environment can be seen as a second skin of the human body especially in today's hyper-connected era. By connecting one's body to the internet through various gadgets, for example, by using a mouse and keyboard in the early years and VR helmet and Google Glasses in today's times, technology gives people a chance to de-construct their body and re-assemble it as an AVATAR throughout the Internet in a parallel digital universe. The manner in which each digital embodiment (IP address) attaches itself to the network of internet/cyberspace, can be equated with individual beings as machines with embedded desires adhering to the smooth surface of a "Disembodied ***Body Without Organs"***. This idea of individual entities relates to the notion of "***Monadology***"[5] proposed by Gottfried Leibniz (Leibniz, 1714).

5 The Monadology is one of Gottfried Leibniz's best-known works representing his later philosophy by sketching in some 90 paragraphs a metaphysics of simple substances, or monads. As far as Leibniz allows just one type of element in the building of the universe, and this unique element has been 'given the general name monad or entelechy' and described as 'a simple substance' (the text was cited from: https://en.wikipedia.org/wiki/Monadology#Text).

A sophisticated network constructed by the Monad can be equated with a complex system composed of small intelligent entities in a system. In other words, either a single cell of a body, a bird in a swarm, a tiny dust particle in the air, or a planet in the universe, all follow certain dynamic principles to maintain their interrelationships and thus maintain the homeostasis of the overall network. From this perspective, both notions of understating "architecture as a body" or "the body as architecture", implies space being a refined object composed of multitudes of intelligent entities. This research also considers this notion as an inspiration to generate the proposed organic body-like architecture.

Is now the time to take both Reality and Virtual Reality into account while conceiving spatial/architecture designs?

It is no longer considered a magical moment if a person is omnipresent in different spaces at the same time using the Internet. Once you are "on-line", you can be present in any virtual environment playing the role of as many different characters as you like in the so called "parallel digital universe". The Internet or Cyberspace has become common in people's daily lives for several decades now. Nonetheless, Virtual Reality, although a part of Cyberspace, now refers more to an immersive and relatively tangible experience by utilizing wearable technology. In other words, Virtual Reality is not completely a different concept than Cyberspace, but with Internet connectivity, the being virtually omnipresent idea, can now be achieved in a relatively more tactile and sensory environment with feelings enhanced with the use of wearable gadgets. Within the Internet environment in a conventional on-line game, you might see yourself as an AVATAR inside the world through the interface of the "**SCREEN**" in front of you, but with electronic gadgets like Google glasses, you are able to envision the whole surroundings as a simulated environment through another interface of the "**LENSES**" which makes you feel more authentically engulfed inside this Virtual Reality environment. This relates to Marcos Novak's idea that "the Cyberspace itself is architecture, but it also contains architecture". Regardless of whether physical space contains Cyberspace or the other way around, it has become "an architecture nested within architecture" (Novak, 1991). It is now considered inadequate to ignore the true sense that people gain from the world of Virtual Reality and to claim that Virtual Reality is totally fake. It is now the time to confront the integration of Virtual and Real to seek an equal/dynamic balance between the two since both conditions occupy almost the same time and space in people's lives.

How to materialized an organic body-like space as an interactive architecture?

"How to materialize" a body-like interactive architecture has always been a difficult issue for both interactive and "organic body-like" architectures. But this is one of the main challenges this research would like to explore. A common analog for comparing

technological devices to an organic body is to envision the body being composed of sensor and actuator parts and the brain being the seat of computation, which acts as a commander/orchestrator. By observing the current development of body parts in interactive architecture, which mainly comprises of actuating systems, one can delineate the features in two different categories, "**Naturalized**" and "**Motorized**". The "**Naturalized**" features refer to actuation utilized by the natural material properties to achieve kinetic movement; the "**Motorized**" functions indicate those requiring electricity to perform relatively strong and powerful kinetic mechanical actuations. The "**Naturalized**" systems tend to be more sensitive and energy efficient but such engineered materials are normally structurally weaker to support architectural scale built work and thus tend to be deployed as non-structural building skins; the "**Motorized**" ones are sufficient enough for holding the bigger construction and but suffer from disadvantages of being relatively less sustainable as regards energy consumption and take up larger proportions of space for performing their tasks. Therefore, the research questions if it would be favorable to develop a Hybrid condition wherein the advantages of each system can be considered for developing Interactive Architecture. As for the notion of the brain operating as the centralized commander to control the sensing and actuations of a body, it is quintessential to state that the natural brain works in the manner of a highly distributed system. The main components of the intelligence of the brain that makes you think, sense, and react are the brain cells or so-called the neurons. They are constructed nearby and form the cerebrum for the reason to get the extreme protection of the skull by nature but it doesn't make the cerebrum a centralized controlling machine because of their close location. In fact, they are assigned to different specific tasks through networking communications and to eventually have the ultimate emerging decision which makes it actually akin to a more de-centralized system in terms of its operational logic[6]. For the proposed embedded intelligence based organic space, the computation would thus acquire a distributed systemic quality as regards its control systems, akin to a swarm of agents. This property will also insure the performance of the entire system to be intact even while any one of the constituting entities of this space is out of operation.

6 Please refer to the website for further understanding of brain and neuron: https://en.wikipedia.org/wiki/Neuron

Biology (Chapter 5):

What are the current developments in Biomimetic design developments in the context of "Organic" or "Bio-inspired" architectures?

Investigations into the current Biomimetic design developments of "Organic" or "Bio-inspired" architectures, lead to their categorization into "**Morphological**", "**Material**", and "**Behavioral**". As for the "**Morphological**", various digital approaches of either using 3D modeling software to create the organic-looking shapes or applying generic algorithms from "Chaos Theory" for organic form-finding is covered in this chapter. The "**Materials**" part under the tag of organic and bio-inspired designs focus on material properties, which include the development of smart materials, transplanting bio-organs into physical architecture or utilizing biomimetics in conjunction with advanced digital fabrication techniques. In the section of "**Behavioral**" aspects, swarm logic is applied as a generic form-finding solution to crystallize real spatial objects. The section also elaborates upon some experimental architectural projects, which translate swarm simulation based outputs into advanced applications such as generating intelligent building blocks as basic elements composing the entire architectural body. A wide range of studies and research have been covered in this section to give a clear picture of what is the current status quo of "**Organic**" and "**Bio-Inspired**" **Architecture** as a Biomimetic or Bio-ARCH resource.

What novel application of natural/biological systems based knowledge can be applied within architectural design instead of merely focusing on the prevalent form based mimicry approach?

Janine Benyus, a biologist who coined the term "Biomimicry" once stated in a public TED talk[7] that there are three levels of learning from nature. The first one is to learn from the appearance/form of natural organisms; the second is to learn the processes of natural growth and evolution; and the last is not only to learn from nature but to actually integrate with natural eco-systems. After spending years into mimicking animal organic forms with the help of digital sculpting or algorithm generation, it can be sufficiently claimed that much progress has been achieved in mimicking such outward appearance. A shift to the next level of learning from nature: understanding "Process" is thus our challenge now. John Frazer in his influential publication, "***An Evolutionary Architecture***" (Frazer, 1995), simply but explicitly stated: ***"what we are***

7 Please find the link of the Janine Benyus' TED lecture here: https://www.ted.com/talks/janine_benyus_biomimicry_in_action

evolving are the rules for generating forms, rather than the forms themselves". Keeping in line with Frazer's proposition, to understand processes of growth, evolution, and development in nature it is thus deemed essential to conceive a rule-based design framework as a new way of architectural design thinking of Organic Architecture. We should thus look fundamentally into the principles of morphogenesis to understand how natural organisms end up having differentiations even though they share the same gene toolkits as an essence of the proposed organic architectural design framework. The research hence makes serious investigations into Evolutionary Development Biology (Evo-Devo) which offers an interesting insight into evolutionary principles. Intriguingly, the research is able to extract three fundamental principles from Evo-Devo intended to be translated and applied systematically to the proposed organic body like architecture: "**Simple to Complex**", "**Geometric Information distribution**", and "**On/Off Switch and Trigger**".

§ 1.3 Research Objective

The research apart from addressing the main and sub-questions mentioned above points towards future directions for Interactive Architecture (as active organic Bio-architecture) and strongly provokes researchers and architects to dedicate themselves to this realm.

By extracting the three biological morphogenesis principles of "Simple to Complex", "Geometric Information Distribution", and "On/Off Switch and Trigger", and translating them into three design rules of "Componential System", "Collective Intelligence", and "Assembly Regulation", the primary objective of the research is the following: To develop a rule-based design framework for interactive Bio-architecture, which can interact and improvise its performance in response to its context in real-time. This will encompass active reconfiguration of space in accordance with user demands akin to a living organism.

Extending the discussion of the research questions, the study sets up a rule-based design framework by translating the three crucial morphogenesis principles from Evo-Devo (Carroll, 2005) into design rules for Interactive Bio-Architecture. The "**Simple to Complex**" idea was translated to deploy the notion of a modularity idea in the form of a "**Componential System**". This relates to the fact that complex shapes within the animal kingdom are composed out of the repetition of simple, self-similar modules. Following this componential idea, the "**Geometric Information Distribution**" principle was abstracted as a rule set fostering "**Collective Intelligence**". This relates to the

context of cellular development and the manner in which a distributed information system regulates the morphological evolution of successive cells in order to create diverse organs. A collective intelligence protocol which aids in the real-time growth and evolution of building components from a morphological and behavioral perspective is thus set up. The "**On/Off Switch and Trigger**" principle, which regulates the process of morphogenesis in living organisms, is utilized as a strategy for conceiving protocols for the development of an informed architecture comprising of numerous smart autonomous entities: "**Assembly Regulation"**. These principles are exemplified upon in greater detail in the first half of Chapter 6. The research is thus primarily concerned with the intricacies of processing, generating, transforming, and communicating principles rather than having an outwardly focus on the generation of organic form.

Organic + Embodiment + Bio-Architecture = Componential System + Collective Intelligence + Assembly Regulation

Apart from the aforementioned bio-inspired rule based principles, what is the practical end goal/output that this biomimetic Interactive Bio-Architecture can provide? This design framework is essentially aiming to produce a user-centric reconfigurable space, which responds to the users' varying ergonomic and activity patterns through a 24 hrs. cycle. Unlike former developments in Interactive Architecture that mostly focused on environmental response, which gave the users inside the space a relatively indirect influence, this research concentrates on the user-centered design to deal with the real-time responsive space, which will have a strong and direct impact on the people occupying it. It is the core idea of this study to use a minimum footprint of space to fulfill the maximum activity based spatial requirements of the users, thus encouraging a sustainable space usage strategy. By creating such a user-centric reconfigurable space, it not only ensures that the users can experience optimal spatial usage but could also lower the price of real estate for residential space, thus providing a new perspective to solving critical problems of urban.

Sub-Objective:

Considering that architecture can have its own intelligence and own behavior implies establishing new relationships between it and human bodies. This hypothesis already marks a reversal of conventional design thinking in conceiving architecture while challenging our perception of architectural space.

Taking inspiration from Marcos Novak's Liquid Architecture (Novak, 1991) and Kas Oosterhuis' HyperBodies (Oosterhuis, HyperBodies: Towards an E-motive Architecture, 2003), this research would like to address the future of cognitive architecture with embodied intelligence how it could forge a new relationship between its own

living creature-like attributes and its human occupants. Such spatial evolution can certainly become a probable future scenario considering the fast pace of technological development coupled with advanced research in the domain of Smart Living solutions using Artificial Intelligence and Machine Learning. It would thus not be surprising to witness a time in the near future when space embodies its own intelligence.

§ 1.4 Research Methodology and Proof of Concept

To achieve the research objective, a wide range of inter-disciplinary studies were conducted. These included explorations within the domains of architecture, contemporary technological innovations, interactive art, media culture and social contents, associated with the topics of interaction, computation, and biology. This wide body of knowledge apart from operating as literature review helps in providing abundant resources for subsequent research for the younger generation of architects who wish to dedicate themselves in investigating the domains of interactive, computational, and or bio-inspired design in architecture. By extracting, organizing, translating, and mastering the above knowledge, a comprehensive design framework: "**HyperCell**" is derived for developing organic body-like architectures.

Subsequently, experimental design projects based on the "**HyperCell**" design framework were conducted as proof of concept. These, are divided into two major parts, the "**User-For**" and the "**User-Less**". The first series of the experimental design projects, "**User-For**", was aimed at conceiving a user-oriented re-configurable space idea in the form of a furniture system, termed as "**HyperCell**". Hypercell builds upon the concept of a transformable building component similar to the traditional Asian tangram concept. A series of "**HyperCell**" furniture applications are illustrated in this part of the study. "**User-Less**" is the second part of the experimental design projects addressing the topic of a non-utilitarian with a central hypothesis, which considers space akin to a living creature with embedded intelligence and behavior which challenges the human body towards adopting novel movement and instigates a shift in perception. Two major projects under "User-Less" were conceived and executed; "**Ambiguous Topology**", which leans towards an immersive new-media driven spatial experience and the "**HyperLoop",** a scaled prototype of an interactive pavilion design. Both projects were a part of "**Metabody**", a European Culture Project which, focused on the inter-disciplinary development of an Intra-active architectural space (Elaborated upon in Chapter 6).

Two kinds of experiments, one engulfing a real-time utilitarian response and the other covering a self-evolving behavioral interaction are conducted as proof of concepts of the research objective. These experiments (HyperCell[8], Ambiguous Topology[9], HyperCell Pavilion) are elaborated upon extensively in Chapter 6.

§ 1.5 Research Outline

The research is structured explicitly, providing each chapter within its own particular focus. After an overview of the trajectory of the project, which extends into Chapter 2, the three major topics of "**Computation**", "**Embodiment**", and "**Biology**" are sequentially elaborated separately, yet in an intimate interconnected fashion through Chapters 3-5. In conclusion, a design framework for Interactive Architecture for developing novel Organic Architecture is proposed in Chapter 6. An application of this Design Framework via the projects HyperCell furniture system, Ambiguous Topology and the Prototype of HyperLoop Pavilion serves as proof of concepts in Chapter 6. Chapter 7. The research subsequently points towards several ideas and directions for future research development not only as a reference to other researchers interested in this interdisciplinary exploration but also as a reminder towards the vital contributions made by this research to the three intriguing topics.

Chapter 2-

Chapter 2 elaborates upon the contributions of the avant-garde architecture group, "Archigram", from the 60's and challenges the long-term fundamental attributes associated with architecture; Utilitas, Firmitas, and Venustas. An alternative focus on developing dynamic, fluid, and interactive attributes of Architecture, which focus on today's transient societal, the environment, and user based issues. Post this, an introduction to the evolution of Interactive Architecture mainly focusing on shifting

8 Biloria, Nimish & Chang, Jia-Rey. (2013). Hyper-Morphology: Experimentations with bio-inspired design processes for adaptive spatial re-use. Proceedings of the eCAADe Conference Volume No.1, 2013 (TU Delft) (pp. 529-538). Delft: eCAADe and Faculty of Architecture, Delft University of Technology.

9 Chang, Jia-Rey, Biloria, Nimish, & Vandoren, Dieter. (2015). Ambiguous Topology from Interactive to Pro-active Spatial Environments. *Proceedings of the IEEE VISAP'15 Conference: Data Improvisation* (pp. 7-13). Chicago: IEEE VISAP.

the emphasis of Interactive Architecture as associated with environmental conditions as a façade/skin system to a more user-oriented usage is presented. Moreover, the research categorizes the current Interactive Architecture developments in accordance with their actuating system; "Naturalized" and "Motorized" in order to assess the pros and cons of both. Apart from the designer's viewpoint concerning spatial usage, the practical utilization of space from the users' point of view is also elaborated upon via case studies and design projects. A series of developments within the domain of bio-inspired design were included in this Chapter. A connection to the latest research developments in Evolutionary Development Biology is thus put into context for illustrating the potential usage of this organic body like architecture. Also, a series of design projects; HyperCell Furniture relating to the HyperCell design framework is elaborated upon sequentially. Chapter 2 concludes with the design projects, "Ambiguous Topology" and "HyperLoop", outlining the next level of artistic discussions on cognitive architecture with its own intelligence and behavior as a proactive space and how to set up a new relationship with this kind of living creature like space.

Chapter 3-

Chapter 3 exhibits the evolution of computational applications in Architecture. The chapter categorizes the different approaches of harnessing computational technologies by designers as "**Form Sculptor**", "**Form Generator**", "**Form Animator**", and "**Form Interactor**". "**Form Sculptor**" indicates the category wherein architects use 3D modeling software as a tool for form modeling in a top-down aesthetics driven decision-making capacity; The "**Form Generator**" category refers to the usage of computational technology deploying generative algorithms to assist architects within the form-finding process (current prevalence of parametric or algorithmic design); The "**Form Animator**" category refers to computational experiments which tend to identify how organic bodies were formed and how they evolve while they are within specific environmental conditions to generate their resulting forms, while "**Form Interactor**" refers to a category wherein computational applications are used for dynamic interaction with the surroundings to evoke an active, cognitive approach. The Form Interactor category is what the direction which the research exploits further.

Chapter 4-

Chapter 4 emphasizes on the topic of "**Embodiment**" with a deep focus on the concept of "**Body Extension**" as suggested by Marshall McLuhan (McLuhan, Understanding Media: The Extensions of Man, 1964), "**Body Without Organs**" from Gilles Deleuze and Félix Guattari (Deleuze, G., & Guattari, F., 2003). "**Body Extension**" and its

philosophical linkage to a virtual space, as well as the "**Body Without Organ's**" and its philosophical linkage with the world composed of Monads as proposed by Gottfried Leibniz's Monadology (Leibniz, Monadology, 1714), refer to the same principle of a network-like structure with the smallest entities constituting the surface possessing exerting highly synergistic, fullerene-like influential forces on each other. Apart from the theoretical discussion on the body relating to reified, embodied and wearable technology, the focus subsequently shifts to the discussion between Virtual and Real and the current developments of Hi-Technology gadgets such as Virtual Reality and Augmented Reality devices. Speaking about Cyberspace and Virtual Reality, these can be seen as evincing the first intentions of generating Interactive Architecture through software and games like SIM City. After years of developments in the physical computing world, with devices such as Arduino, artists and architects now have the opportunity to bring the virtual kinetic/interactive idea into the real world. Since then, rapidly increasing numbers of interactive spatial installations/architectural designs relating to physical computing were created. These have been categorized in this Chapter in two major divisions of "**Naturalized**" utilizing natural material properties, and those that are "**Motorized**" relying heavily on electronically driven mechanical systems. A novel thinking driven by the idea of collective intelligence involving the merger of **Naturalized** and **Motorized** systems into an efficient hybrid system for conceiving interactive architecture might become the next step for a technological breakthrough.

Chapter 5-

Chapter 5 elaborates upon the topic of biology or bio-inspired/Biomimetic design. Numerous current developments are featured under three major divisions in this Chapter: "**Morphological**", "**Material**", and "**Behavioral**". The "**Morphological**" aspect looks into the relationship between organic form and artificial architectural forms comprising methods of 3d modeling and generative algorithms in the form-finding process. The "**Material**" category involves explorations involving the usage of bio-materials (for instance transplanting natural flesh as architectural components), and the biomimicry approach including materialization aspects involving digital fabrication techniques and contemporary scientific principles from physics or chemistry. The "**Behavioral**" factor is akin to the logic of swarm behavior wherein every building block becomes an intelligent entity constituting the whole architectural body. Instead of researching optimization based solution for generating a static form, the research involves evolving real-time adaptive kinetic architectural bodies that can respond to different conditions through dynamic optimization. Unlike the most common approach of mimicking organic form, this research paid attention to the principles of morphogenesis, specifically Evolutionary Development Biology (Carroll, 2005). The

research explicitly involves extracting growth and adaptation rules from such studies and applying it to Interactive Architectural design. Three biological morphogenesis principles of "Simple to Complex", "Geometric Information Distribution", and "On/Off Switch and Trigger", are translated into three design rules of "Componential System", "Collective Intelligence", and "Assembly Regulation". These are explicitly identified upon in this Chapter and elaborated upon in Chapter 6.

Chapter 6-

Chapter 6 is a summary of the aforementioned domains of **Computation**, **Embodiment**, and **Biology**, and merging the findings via principles derived from Evo-Devo to develop a design framework, "HyperCell", for developing Interactive Architecture as an authentic form of Organic Bio-Architecture. The rules comprising this design system: "**Simple to Complex**", "**Geometric Information Distribution**", and "**On/Off Switch and Trigger**" are all transformed and applied towards developing "**Componential System**", "**Collective Intelligence**" and "**Assembly Regulation**" logics. To prove that the architecture design can follow this design framework to create novel and useful usage of space, a series of **HyperCell** experiments were conducted in the form of experimental design projects elaborating upon the potential flexibility and efficiency of this real-time adaptive furniture system. Extending the discussion of creating an organic body-like interactive architectural space to a techno-artistic level of making a cognitive, smart space having its own intelligence and behaviors, the research involved further developing an immersive interaction based project: "**Ambiguous Topology**", and a scaled prototype of an interactive pavilion, "**HyperLoop**". These projects further open up a novel direction of design development challenging the norm where architecture relates to solid, concrete and static built form.

Chapter 7-

In Chapter 7, the research categorizes the entire narrative into three vital features: "**information**", "**improvisation**", and "**integration**", and concludes with the idea of "**intelligence**" as a merger of these features. Future recommendations are proposed in the form of **Software**, **Hardware**, and **Design Thinking methods**. In conclusion, while addressing **Software**, the research proposes a game-like structure in the form of a design tool embodying the proposed rule-based design framework which can even combine VR and motion tracking technology. It is the vision of the author to realize the **HyperCell** furniture component as physical **Hardware** extension of the research, go beyond developing such components for interior purposes but develop them as real physical building blocks constituting architecture. Intelligence driven Self-assembly could become an active feature

whereby both construction and disassembly of the space is automated. In this case, a hybrid material merging the advantages of naturalized and motorized systems would naturally be needed to work in synergy. Concerning **Design Thinking Methods**, the HyperCell design framework is used to inspire people to further the componential idea based proposed bio-inspired architecture development. It is not necessary to follow the exact principles provided in this research, but it is crucial to stimulate this kind of interdisciplinary and robust design thinking in architectural design. The research ultimately envisions a near future comprising various spatial and product based options customized to user choices akin to the "**HyperCell**" based outputs proposed in this research.

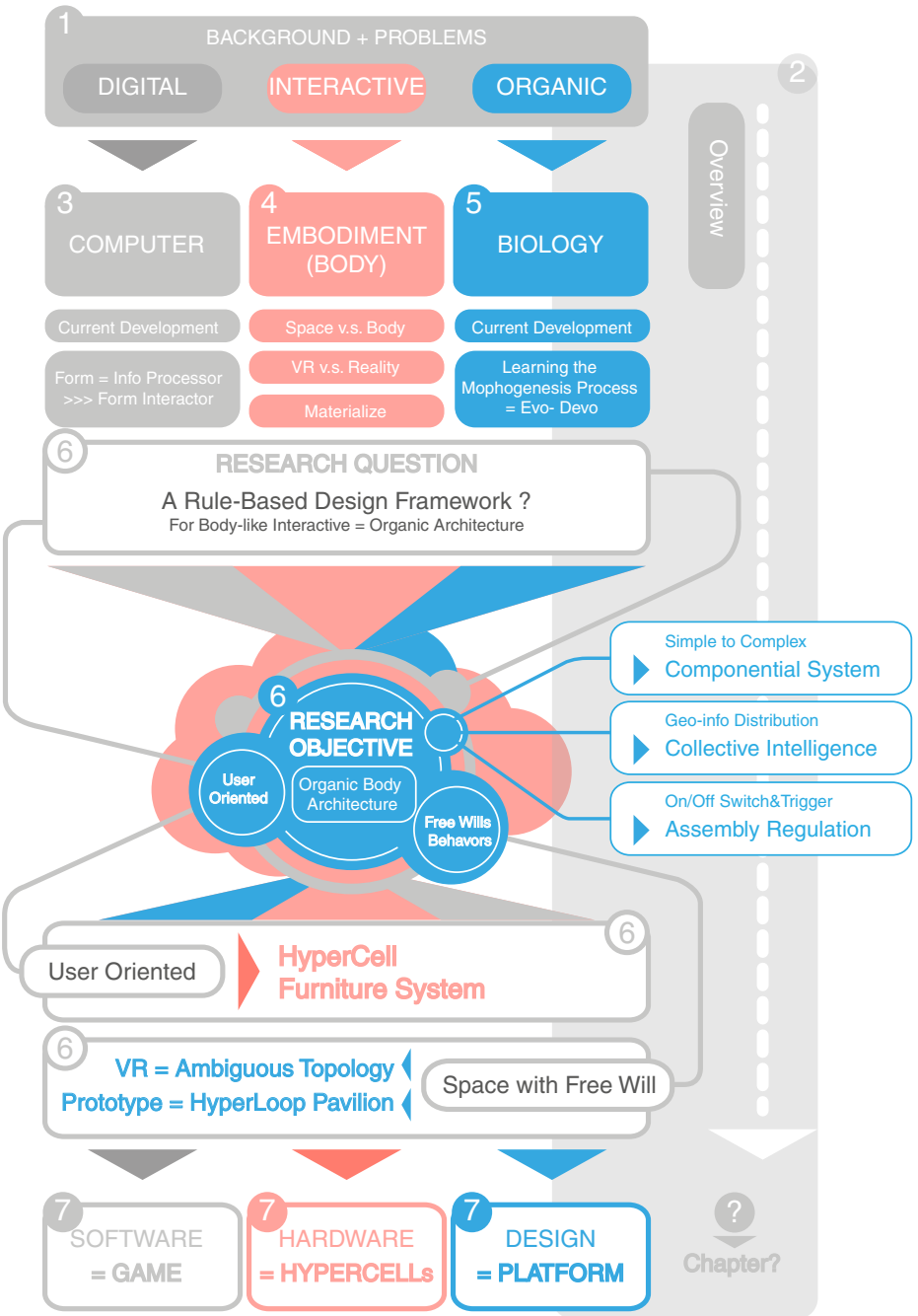

FIGURE 1.1 Overview of the Research Framework Map.

TOC

References

Carroll, S. B. (2005). *Endless Forms Most Beautiful: the New Science of Evo Devo.* New York: W. W. Norton & Company, Inc.

Deleuze, G., & Guattari, F. (2003). *Anti-Oedipus: Capitalism and schizophrenia.* London: Continuum.

Frazer, J. (1995). A Natural Model for Architecture/ The Nature of the Evolutionary Mode. In J. Frazer, *An Evolutionary Architecture.* London: Architectural Association.

Leibniz, G. W. (1714). *Monadology.* (J. Bennett, Trans.) Retrieved from http://www.earlymoderntexts.com/assets/pdfs/leibniz1714b.pdf

McLuhan, M. (1964). *Understanding Media: The Extensions of Man.* New York: McGraw-Hill.

Novak, M. (1991). Liquid Architectures in Cyberspace. In M. Benedikt, *Cyberspace: First Step* (pp. 225-255). Cambridge: The MIT Press.

Oosterhuis, K. (2003). *HyperBodies: Towards an E-motive Architecture.* Basel: Birkhäuser.