A CONCEPTUAL MODEL PROPOSAL OF DYNAMIC ARCHITECTURE WITH DYNAMIC INTERNAL WALLS AS INTERACTION INTERFACE

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

ELİF NADİDE GÜR

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF ARCHITECTURE
IN
ARCHITECTURE

DECEMBER 2018

Approval of the thesis:

A CONCEPTUAL MODEL PROPOSAL OF DYNAMIC ARCHITECTURE WITH DYNAMIC INTERNAL WALLS AS INTERACTION INTERFACE

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ABSTRACT

A CONCEPTUAL MODEL PROPOSAL OF DYNAMIC ARCHITECTURE WITH DYNAMIC INTERNAL WALLS AS INTERACTION INTERFACE

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December 2018, 120 pages

Dynamic Architecture first appeared in 20th century in the field of architecture and have been seen under various names over time such as Transformable Architecture, Responsive Architecture, Adaptive Architecture, Intelligent Architecture and so on. Each of them are specialized on their abilities of responsiveness, transformation and intelligence in accordance with the economic, functional and energy requirements. The reason why Dynamic Architecture is developing fast is that it the follows the latest improvements in the field of electronics, structural engineering and computational sciences. In the light of the latest developments, the aim of this thesis is to propose a conceptual model of an inclusive and advanced dynamic architectural space, which has dynamic internal walls as interaction interface to strengthen human-building interactivity with intelligent behaviors. As the recent developments in artificial intelligence and structural engineering make advanced architectural environments possible, multi-agent dynamic systems can be used to control ambient intelligence of the space and deep learning algorithms can be used in interactive interface to communicate more interactively with users. With this proposal, a space can become more interactive by gaining the capabilities of dynamism and intelligent behavior, which can push the dynamic building term one step forward by improving human-building interactions and it can have its own charactheristics using what it senses and learns. For this purpose, the positive aspects of dynamic architectural terms, construction of dynamic structures and composition of intelligent behaviors of the space are the matters of discussion in this thesis.

Keywords: Dynamic Architecture, Artificial Intelligence, Interactive Interface, Multi-Agent Dynamic System, Deep Learning

ÖZ

İNTERAKTİF ARAYÜZ OLARAK DİNAMİK İÇ YAPI DUVARLARI İLE TANIMLANMIŞ BİR DİNAMİK MİMARLIK KONSEPTİ ÖNERİSİ

Gür, Elif Nadide
Yüksek Lisans, Mimarlık Bölümü
Tez Yöneticisi: Prof. Dr. Ahmet Can Baykan
Aralık 2018, 120 sayfa

Dinamik Mimarlık mimarlık alanında ilk olarak 20. yüzyılda ortaya çıkmıştır ve zaman içerisinde Dönüştürülebilir Mimarlık, Tepkimeli Mimarlık, Adaptif Mimarlık ve Akıllık Mimarlık gibi çeşitli isimlerle görülmektedir. Bunlardan her biri ekonomik, fonksiyonel ve enerji korunumu gereksinimlerine göre, tepki yeteneği, dönüştürülebilirlik ve akıllı olma kabiliyetlerine göre özelleşmiştir. Dinamik Mimarlık çeşitlerinin bu kadar hızlı çoğalmasının sebebi elektronik, strüktürel mühendislik ve bilgisayar bilimlerindeki son gelişmeleri takip etmesidir. Son gelişmelerin ışığında, bu tezin amacı akıllı davranışlarıyla yapı-insan etkileşimini güçlendirmek için interaktif arayüz olarak dinamik yapı iç duvarlarına sahip kapsayıcı ve gelişmiş bir mimari mekan önerisi sunmaktır. Yapay zeka ve strüktürel mühendislikteki son gelişmeler gelişmiş mimari mekanlara olanak sağladığı için, çok ajanlı dinamik sistemleri mekanın ortam aklını kontrol sistemi olarak kullanmak ve interaktif arayüzde derin öğrenme algoritmalarını yapı kullanıcılarıyla etkileşimli iletişim kurmak için kullanmak mümkündür. Bu öneri ile bir mekan dinamik ve akıllı davranışlar kazanarak daha interaktif bir hale gelebilecek ve yapı-insan etkileşimini güçlendirerek dinamik mimarlık terimini bir adım öteye taşıyacak ve algıladığı ve öğrendiklerine göre kendi karakteristiğini kazanacaktır. Bu amaçla dinamik

mimarlığın pozitif yönleri, dinamik strüktürlerin konstrüksiyonu ve mekanın akıllı davranışları bu tezin tartışma konuları olmuştur.

Anahtar Kelimeler: Dinamik Mimarlık, Yapay Zeka, İnteraktif Arayüz, Çok Ajanlı Dinamik Sistemler, Derin Öğrenme

To My Loving Family and My Love

ACKNOWLEDGMENTS

First and foremost, I would like to begin with expressing my deepest gratitudes to my supervisor Prof. Dr. Ahmet Can Baykan, for his intense guidance, patience and sincere support with valuable comments and suggestions throughout the thesis. He supported my investigation on this topic, which I was interested in. Without his critics and wisdom, this study could not have been realized.

I also would like to thank the examining committee, Assoc. Prof. Dr. Ali Murat Tanyer and Assoc. Prof. Dr. Burcu Şenyapılı for their inspiring comments and criticism which provided inspiration for the completion of this study.

This task would not have succeeded without my friends' and family's endless love, encouragement and patience. I would like to express my gratefulness to my mother, Hülya Gür, who always support me during every difficult time of my life, and to my father, Memduh Gür, who believes in my success. Special thanks to my sister, Nilüfer Merve Çelik and Merve Değermenci, who is like my sister also, for their endless love and being with me whenever I need. I am also indebted to my dear love Yiğit Değer for his love, and support, which could provide me peace and happiness.

Besides, I would like to thank my lovely friends, Selcen Yeniçeri, Sena Demirel, Zeynep Gonca Tunçbilek and Meltem Çetiner, who keep my motivation and level of morale high enough during the whole study.

Finally, I must express my gratitude to my grandparents, Veli Açıkalın, Gülsüm Açıkalın and also to my uncle Ahmet Açıkalın for their sincere love and encouragements.

TABLE OF CONTENTS

LIST OF FIGURES

FIGURES

LIST OF TABLES

TABLES

LIST OF ABBREVATIONS

AI Artificial Intelligence

AmI Ambient Intelligence

ANN Artificial Neural Networks

DL Deep Learning

MAS Multi-Agent System

ML Machine Learning

CHAPTER 1

INTRODUCTION

In recent years, Dynamic Architecture is a very popular field of architecture. This study intends to explore the potentials of dynamic architecture, and outlines a vision for the future, constructing a conceptual model of ambient intelligence based on the latest artificial intelligence developments.

1.1. Research Motivation and Problem Definition

The advance in computational technologies, sophisticated algorithms and structural engineering allows the designers to develop various type of dynamic architectural environment proposals. Hence recently, dynamic architectural spaces are not only adaptive or transformable, but also they are interactive and more intelligent. Furthermore, today, computation is not only a medium of designing space but also it is a medium of intelligent space. Hence the intelligent systems and their algorithms to be integrated in such architectural environments becomes very crucial while affecting the dynamism and interactivity of a space.

This thesis studies the integration of the focal points of interactive and intelligent environment with multi-agent dynamic system as a design paradigm which could be basically based on human-building interaction. It will propose new architectural design requirements, supported programming that can be dynamic and changeable according to users and environmental needs.

1.2. Aim and Objectives

In short, current intelligent environments need to be improved and could benefit from latest improvements in artificial intelligence while improving. Thus, the present study is based on the necessity for a new understanding of dynamic architecture as a side of this perspective. It aims to search for a new proposal of dynamic architecture which has the properties of interactivity, dynamism and intelligence. The main aim of this study is to develop a concept model for an interactive intelligent environment through utilizing multi-agent systems and deep learning algorithms. Research objectives can be listed as:

 Investigating the existing Dynamic Architecture models

 Understanding the logic of Dynamic Architecture models

 Developing a new conceptual model of dynamic architectural space advanced with multi-agent dynamic system, which have a cognition of user and environment for an effective human-building interaction

Considering the importance of artificial intelligence for the dynamic architecture and the drawbacks of existing dynamic approaches, a new conceptual model framework, which could compose to the efficient side of each dynamic approaches, can be developed for the improvement of intelligent building understanding.

1.3. Thesis Methodology

There are two main research questions that direct this research:

- How can an interactive architecture be improved with a new conceptual dynamic architecture approach composed by multi-agent systems?

- How can an interactive environment be aware of its users and environment using deep learning algorithms?

Mainly, this research will be conducted in three phases: investigation of dynamic architecture approaches, proposal of a conceptual dynamic architecture model composed by multi-agent systems, the application of deep learning algorithms to the intelligent systems. In detail, the research methodology is based on four steps:

1. An overview of dynamic architectural approaches

2. Establishing a background for the reason of the need of a new concept of dynamic architecture

3. Proposing a new conceptual model of dynamic architecture integrated multi-agent systems

4. Computation logic of deep learning algorithms for the cognition of an architectural environment

1.4. Thesis Structure

This thesis aims to describe the proposed model in four chapters:

Chapter I: Introduction

Chapter I introduce the reader to the thesis while explaining the aim and objectives, methodology and the structure of the thesis.

Chapter II: Dynamic Architecture Approaches

Chapter II is a literature review of the theoretical background on dynamic architectures. It includes the definitions of dynamic architectural approaches and related examples, their spesific dynamism and intelligence properties.

Chapter III: Dynamism of Architectural Environment

Chapter III presents the evaluation of dynamism in the architectural environment and their implementation methods in the architectural environment.

Chapter IV: Intelligence of Architectural Environment

In this chapter, the history of artificial intelligence is declared and the intelligence of dynamic architecture is discovered with the help of examples.

Chapter V: A Conceptual Model Proposal for Dynamic Architectural Environment

Chapter V gives detailed information about the proposed conceptual model of dynamic architecture: its ambient intelligence, algorithms, dynamic components and their designing principles. In addition, advantages and limitations of applying deep learning algorithms to the proposed model are discussed.

Chapter VI: Conclusion

In the concluding chapter, a brief summary of the study with contributions, limitations and suggestions for horizons of dynamic-intelligent environments in architecture is given.

CHAPTER 2

DYNAMIC ARCHITECTURE APPROACHES

This chapter is planned to construct a background of dynamic architecture approaches, which concern more or less the same issue that is creating an intelligent and dynamic system to extend the capabilities of a building for smart and sustainable living. Selected types of dynamic architecture, Interactive and Intelligent Architecture will be presented to the reader with their logic and difference explained in detailed.

2.1. Arrival to the Concept of Dynamic Architecture

> "Architecture has always been known as static, hard and heavy. Architecture in the future will physically adapt to our needs and expectations, because change is a constant process of our time, our environment needs the ability to change "
>
> Christoph Bauder

Dynamic Architecture approaches were born in the early part of 20th century in the light of studies and improvements on computation and artificial intelligence technology. [1]In the architectural field, the developments on artificial intelligence led the idea of designing the building as a living organism in architects' minds. The underlying question of this idea was why the environment is changing continuously over time, the buildings are mostly designed as static objects within changing environment.[2] Inasmuch as, it is well-known that the natural environment has the ability of being alive through its dynamism, which is a a significant part of nature

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[1] Kolarevic B., Parlac V. (Eds.) , (2015), Building Dynamics: Exploring Architecture of Change

2 Pan C. A., Jeng T., (2010), A Robotic and Kinetic Design for Interactive Architecture, SICE Annual Conference 2010, August 18-21, The Grand Hotel, Taipei, Taiwan

with continious ongoing processes such as the seasons of the year, the formation of fruits, high and low tides and so on.

The concept of dynamic architecture is firstly appeared in the field of architecture with the terms of responsive and adaptive architecture in 1960s and 1970s.[3] After that, in the 20th and 21th century, many related architectural terms on dynamism, movability, transformability and adaptivity are proposed as Dynamic Architecture, Adaptive Architecture, Responsive Architecture, Intelligent Architecture, Kinetic Architecture and so on. Despite their close relation to each other because of association with shape changing and intelligence, there are some differences between them. Although some examples of them overlap in more than one category, all of these dynamic architectural approaches that have been put forward so far, could be examined in four main categories as shown below:

1.Responsive-Adaptive Architecture

2.Transformable Architecture

3.Interactive Architecture

4. Intelligent Architecture

[3] Kolarevic B., Parlac V. (Eds.) , op. cit. p.2

2.1.1. Responsive-Adaptive Architecture

Responsive-adaptive architecture is based on the adaptation of architectural components to fit vary social functions and environmental stimulus while occupancy. Architectural components should be designed to be easily altered and modified to respond to different conditions at a place. Initial proposals of Adaptive-Responsive Architecture are towards to energy demands of the building envelope. Especially in the late 1990s, with technological innovations, architects and engineers started to incorporate electronics and mechanics to the building envelopes to manage energy use with integrated systems to the façades.[4]

Figure 2.1. Adaptive Architecture, Starlight Theater, Uni-Systems Engineering

< Source: Uni-Engineer, retrieved from http://www.uni-engineer.com/starlight-theatre.html, 16 August 2018>

Although the researches and developments on Responsive-Adaptive Architecture are mostly seen at the façade of the buildings, adaptivity and responsiveness are not limited to building envelopes only in these days. As an example of it, as shown in Figure 2.1., the project named Starlight Theater by Uni-Systems Engineering has 6 roof panels from the perspective of the audience for seeing the sky. The roof of the building, which opens when observing the sky by audiences and closes when having bad weather, has an electro-mechanical system, which drives the roof panels and a

[4] Kolarevic B., Parlac V. (Eds.) , op. cit. p.5

hydraulic mechanism, which supports the weight of each panel for guaranteing audience safety.[5]

2.1.2. Transformable Architecture

Transformable Architecture was born with the idea of reducing the environmental footprint of humans after covering almost all of the earth with buildings and artificial structures. Transformable Architecture contains transformable volumes, internal configurations, structure and forms for creating multi-purpose and changable spaces in minimum sizes. Architectural components should be designed to be easily changable to alter and transform to new shapes, forms and charactheristics in a controlled manner, which focuses on mainly functional, environmental, aesthetic and economic requirements of a space.

Figure 2.2. Transformable Architecture, M-Velope Transformer House, Michael Jantzen

< Source: Inhabitat, retrieved from https://inhabitat.com/transformable-mvelope-by-michael-jantzen/, 17 August 2018>

As shown in Figure 2.2., the design of Michael Jantzen M-Velope Transformer House could be a successful example of Transformable Architecture. In this example, he proposed a structure created from sustainable materials, which can be easily transformed into different usable forms to design more smaller and usable spaces depending on needs. A small space like this structure (230 sq foot) could be rearranged into various forms through its movable wooden panels on the steel frame. Interior benches of the structure could provide a workspace as well as sleeping platforms and when they folded away, the structure could be open up for more rooms.

5 Uni-Systems Engineering, (2018, August 16), Starlight Theater, retrieved from http://www.uni-engineer.com/starlight-theatre.html

2.1.3. Interactive Architecture

The theoretical background of interactive architecture is based on cybernetics in the 1960s. With having a strong foothold of cybernetics in the 1990s, interactive architecture also became more feasible in both economical and technological way.[6] Interactive Architecture provide to its users an appropriate space for their needs and goals while allowing them to have a bottom-up role in (re)configuring the space. In other words, interactive architecture subjects mainly creating a changable space according to changing demands of users within the contextual framework of human-building interaction.

Figure 2.3. Interactive Architecture, Graz Modern Art Museum

< Source: Arkitektual, retrieved from http://www.arkitektuel.com/kunsthaus-graz/, 20 August 2018>

As an example of Interactive Architecture, Graz Modern Art Museum shown in Figure 2.3., has a translucent double-curved acrylic surface as an intelligent skin, which is capable of displaying information and relating interactively with users. While it's skin is an electronic media façade, which can provide a creative and provocative engagement with cultural and urban contexts, its interior design is also effective to ensure flexilibilty and ephemerality for handling of exhibition projects.

As interactive architecture, similar to responsive-adaptive architecture, also meets the user requirements or needs, interactive architecture could easily confused with the term of Responsive-Adaptive architecture. The main distinction between them is based on the relationship between human and space. While responsive-adaptive architecture is defined as "networked structure that senses action within a field of

[6] Fox M., Kemp M., (2009), Interactive Architecture, p. 13

attention and responds dynamically with programmed and designed logic"[7], interactive architecture is defined with circular interaction between two systems instead of simply reaction.[8] Although both of them response with similar dynamic actions of components, a response in interactive architecture should be seen as a part of the overall scenario of an interaction rather than a reaction [9] There shoud be feedback loops in interactive architecture, as Usman Haque, who is an architect and artist designs interactive architecture systems and researches, mentioned "They can converge on a mutually agreeable nature of feedback: an architecture that learns from the inhabitant just as the inhabitant learns from the architecture". Hence the intelligence of an architectural environment could gain the ability of having a communication through each mutual feedbacks. Both positive and negative feedbacks could give a chance to the environment changing itself continiously.

Figure 2.4. E-Motive House, Kas Oostherhuis ,ONL The Innovation Studio

< Source: ONL Studio, retrieved from http://www.onl.eu/projects/e-motive-house, 17 August 2018>

As an example of this mutual communication, in 2002, Kas Oosterhuis proposed E-Motive House, an interactive house shown in Figure 2.4., with emotions. It can be able to construct emotional relationship between the house and users while being a " reactor" as well as an "actor".[10] Then following this design project, in 2003, Kas Oostherhuis and his research group constructed a programmable building prototype "Muscle", which reconfigures itself mentally and physically with its individual

7 Philip Beesley, (2006), Responsive Architectures: Subtle Technologies

8 Fox M., Kemp M., op. cit. p.14

9 Kolarevic B., Parlac V. (Eds.) , op. cit. p.13

10 Kolarevic B., Parlac V. (Eds.) , op. cit. p.10

charactheristics. "Muscle" is an active structure, which responds to a programme. Thus, they led to arise the term of "Programmable Architecture", which studies the intelligent programmed structures that respond according to the commands derived from the user-environment interactions .

2.1.4. Intelligent Architecture

Intelligent Architecture has a progressive history that improves parallel with the development of intelligent control systems of building operations after 1980. Furthermore,in the 1990s, intelligent environment research accelerated significantly by following the latest advancements in artificial intelligence[11] such as neural networks, fuzzy logic, expert systems and genetic algorithms, and over the past 30 years, many different type of buildings have been labelled as "intelligent" buildings.[12] Although there is no single definition of the term of ‘intelligent building’ accepted worldwide[13], mainly ‘intelligent building’ refers to the ability of a building to respond to the changing stimulus of users and environment in real time according to the received and then processed information.[14]

Figure 2.5. The Tower at PNC Plaza

< Source: Buro Happold, retrieved from https://www.burohappold.com/projects/the-tower-at-pnc-plaza/, 20 August 2018>

[11] Lee, J.H., Hashimoto, H., (2001), Intelligent Space-Concept and Contents, Institute of Industrial Science, University of Tokyo, Komaba 4-6-1, Meguro-ku, Tokyo, Japan

[12] Clements-Croome, D.J., (2013), Intelligent Buildings: Design, management and operation. London: ICE Publishing

[13] Wang S., (2010), Intelligent Buildings and Building Automation

[14] Dwyer T., Kimpian J., Tang L.C.M., (2013), Building and virtual information modelling in intelligent buildings, The Journal of Intelligent Buildings

The main concerns of intelligent buildings are being functional according to energy consumption, performance efficiency and also corresponding to user needs, well-being, the aims of an organisation and long term aspirations of society.[15] Intelligent buildings could manage to these aims with the help of integrated information systems (Intelligent Building Management Systems-"iBMS").[16] As shown in Figure 2.5. and 2.6., The Tower at PNC Plaza could be managed to integrate engineering systems around a core theme; efficient and green design. The architects of this building developed two key features, a fully automated double-skin façade and a solar-power chimney, which work symbiotically to create a highly energy efficient building with passive design strategies.

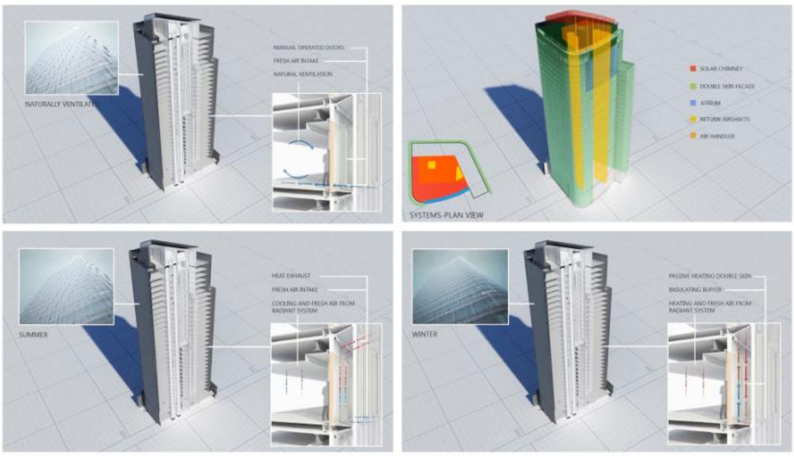

Figure 2.6. The Tower at PNC Plaza iBMS

< Source: Buro Happold, retrieved from https://www.burohappold.com/projects/the-tower-at-pnc-plaza/, 20 August 2018>

Natural ventilation is managed by this double-skin façade, which has a 75 cm cavity between inner and outer window walls. Moreover, blinds set between two walls could reduce glare and heat without blocking daylight and view of the outside. And the solar-power chimney composed of two vertical shafts within the building core, provides to heat, cool and ventilate The Tower with minimal energy use.

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[15] Clements-Croome D., (2014), Intelligent Buildings: An Introduction, p.3

[16] Clements-Croome D., Davies G., (Eds.), (2014), Bringing Intelligence to Buildings, Intelligent Buildings: An Introduction, p.15

2.1.5. Intersection View of Transformable, Interactive and Intelligent Architecture

As mentioned above, in the 20th century, the terminology of Dynamic Architecture multiplies according to their focusing issues. Each Dynamic Architecture approach concerns more or less the same issues noted below:

- meet user needs, requirements and goals

- make intelligent decisions

- respond with dynamic (such as movability, transformability) or static reaction

- energy efficiency

Although all of them are related with almost same issues, some of them focusing more on movability or transfomability, some of them focusing more on intelligence and some of them focusing more on human-environment interactions as shown in Figure 2.7. If classified there are three main sub-headings that could be organized according to these differences:

- evaluation of intelligence

- dynamism approaches

- relationship between human and environment

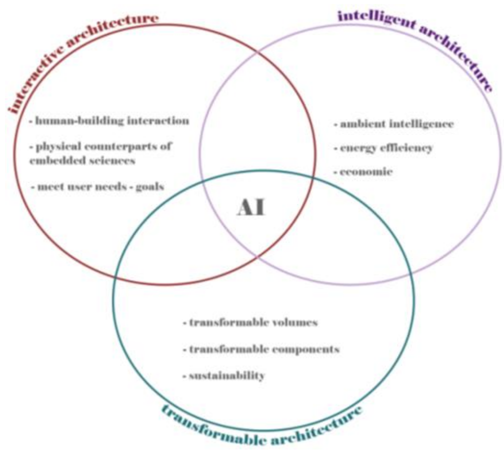

Figure 2.7. Focal Viewpoints of Dynamic Architecture Approaches

Evaluation of intelligence: Like intelligent architecture, interactive architecture also follows the latest projects and trends in AI for constructing intelligence.[17] In other words, similar to the intelligent architecture research, the underlying idea of interactive architecture research is also based on intelligent behavior, which allows to use less energy, to provide for user demands and space flexibility. But compared to intelligent architecture, interactive architecture differently deals with the intelligently behaved physical counterparts of embedded computation rather than dealing with constructing a whole intelligent control system for an ambient intelligence as seen in intelligent architecture.[18] More clearly, the intelligence of interactive architecture is applied mostly in partitions to the architectural environment, such as on façade, on internal components and so on, rather than constructing a holistic intelligent system for an ambient intelligence like an intelligent building.

Dynamism approaches: Furthermore, unlike intelligent architectural research, transformable architecture and most examples of interactive architecture focused more on the dynamic features of a building.[19] Because of this reason, while the developments of interactive architecture is progressing mainly on the way of intelligently dynamic movements of architectural components, the developments of intelligent architecture is progressing mainly on the way of advanced ambient intelligence. Focusing on the dynamic behavior and partially intelligent movements of components rather than a holistic intelligent system cause that the interactive architecture is one step behind according to intelligent architecture in terms of intelligence. But from another perspective, intelligent architecture is one step behind according to interactive architecture and transformable architecture in terms of dynamism and transformations. And also, designing dynamism and transformations and their relations bring into the architectural environment aesthetic, philosophical and conceptual aspects adding to pragmatic understandings.

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17 Fox M., Kemp M., op. cit. p.12

18 Ibid.

19 Pan C. A., Jeng T., (2010), A Robotic and Kinetic Design for Interactive Architecture, SICE Annual Conference 2010, August 18-21, The Grand Hotel, Taipei, Taiwan

Relationship between human-environment: Another main difference between intelligent, transformable and interactive architecture is based the relationship between user and devised space. While intelligent and transformable architecture mainly tries to manage, adapt and respond to the users' and environmental stimulus in one-way linearity, interactive architecture try to manage to construct interactions between human and space as each of them being a participant of the architecture in a two-way circularity. In other words, interaction is an iterative feedback looped process of sensing, computing and responding between users and architectural environments.[20] Therefore, Marcos Novak, who is a Professor at the Department of Architecture and Urban Design at UCLA, claims that the intelligence of interactive architecture with the term of "transactive intelligence", which could manage to transact and transform both user and environment itself.[21] As a result, in terms of reacting rather than interacting, intelligent and transformable architecture is one step behind from interactive architecture.

To conclude, useful aspects of these dynamic architecture types can be composed into a dynamic approach for creating more advanced architectural environments. Being dynamic through advanced intelligent systems improved with latest developments in AI, an interactive architecture could be able to go one step forward and have the ability of the sensing, changing and transforming characteristics as Beesley and his colleagues predicted in 2006 [22] for the next generation of architecture. Furthermore, this dynamic intelligent environment could be able to strengthen the mutual relationship between human and environment as clarified in the next sections of the thesis.

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20 Fox M.(Ed.), (2009), Interactive Architecture: Adaptive World

21 Ćetković, A.K., (2016). The (not so) Intelligent Building

22 Kolarevic B., Parlac V. (Eds.) , op. cit. p. 14

CHAPTER 3

DYNAMISM OF ARCHITECTURAL ENVIRONMENTS

This chapter presents implementation of dynamism in the architectural environment and investigates the role of dynamism in architectural environments.

3.1. Defining Dynamism in Architectural Environment

According to Oxford English Dictionary, "Dynamism" means that "The mode of being of force or energy; operation of force."[23] Dynamism provides the nature to changability for being a sustainable living organism in the most economical way. Like in nature, dynamic movements in architecture could provide to the buildings having the force of changability according to the different type of environmental changes such as users' needs, purposes and climatics.[24]

Dynamism is very strongly related with time, interactions and physics, which could declare balance, speed, accelaration of the movement and mass, weight, form of the objects. To deal with objects under the effect of forces, dynamics is a branch of mechanics, which is a part of physics that deals with movement of object and their causes.[25]

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23 Oxford English Dictionary, (2018, August 22), retrieved from http://www.oed.com/view/Entry/58827?redirectedFrom=Dynamism#eid

24 Megahed N.A., (2017), Understanding kinetic architecture: typology, classification, and design strategy, Architectural Engineering and Design Management, 2017 VOL. 13, NO. 2, 130–146

25 Elkhayat Y.O., (2014), Interactive Movement in Kinetic Architecture, Faculty of Engineering, Tanta University

3.1.1. Actuation of Dynamism in Architectural Environment

As dynamism is based on the force of operation, dynamic movements of architectural components are provided by the power of activation forces. Architectural components could be able to dynamic architectural elements with the help of activation forces. Activation force types of dynamic architectural elements could be classified as motor-based(mechanical), hydraulic, pneumatic and nano-based actuation.(Figure 3.1.)

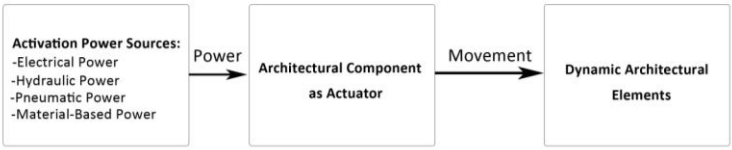

Figure 3.1.Activation Power Forces of Actuators

Motor-based actuation: Each motor-based element could gain actuation through electrical means such as servo-motors.

As an example of motor-based dynamism shown in Figure 3.2., eleven thousand telescopic actuators with internal components are activated by electrical force in Megafaces Pavillion project. Each actuator, which acts one pixel in the whole façade, has a high-power RGB LED lamp. Through these lamps, the façade could display dynamically images or videos.[26]

Figure 3.2. Megafaces Pavillion, The world's first 3d actuated large-scale LED screen, 2014, Asif Khan

<Source: Fox M., Interactive Architecture: Adaptive World, (2009), pp 82>

[26] Fox M.(Ed.), op. cit. p. 82

Hydraulic actuation: Hydraulic systems consist of mainly cylinders connected to spherical joints and a pressure accumulator device, which uses oil. [27] Like hydraulic systems, electro-hydraulic systems work through computer controlled cylinders connected by joints, but they gain the pressure force from electrical ways.

Figure 3.3. Rectractable adaptive shell roof structure with hydraulic system, Bosch Rexroth Company

< Source: Bosch Rexrıth, retrieved from https://www.boschrexroth.com, 20 August 2018>

As shown in Figure 3.3., Bosch Rexroth produced a retractable adaptive roof, which is actuated by electro-mechanical and hydraulic control and drive systems, for multi-purpose usages of arenas.

Pneumatic actuation: Deformable architectural elements can be transformed from a flat form into three-dimensional forms by inflating them under pneumatic pressure or vice versa by deflating. They are able to have two different defined states: inflated and deflated, according to the needs of a space or surface.[28]

Figure 3.4. Pneumatic Responsive Façade, The Media-TIC Building in Barcelona, 2011

<Source:Archello, retrieved from https://archello.com/project/media-tic-barcelona, 12 August 2018>

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[27] Oosterhuis K., Xia X., Sam E.J., (2007), Interactive Architecture

[28] Kronenburg R., (2007), Flexible: architecture that responds to change, Laurence King, United Kingdom

As shown in Figure 3.4., the Media-TIC Building in Barcelona is designed by Enric Ruiz-Geli in 2011 with a dynamic façade, which consists of ETFE air cushions that gain their activation forces from pneumatic actuation. The triangular cushions, which consist of three layers of plastic with two air chambers between them, inflate and deflate to provide sensor-controlled sun shading while responding to the rising temperature outside according to the need of solar energy or shading.[29]

Nano-based actuation: Nano-based architectural elements causes nanotechnology-based dynamism according to their spesific material properties. This type of dynamic elements are actuated generally by three ways: electrical, light or heat. According to their actuation types, they can mainly be classified as electrochromic materials, photochromic materials or thermochromic materials. [30]

(a)

(b)

Figure 3. 5. Hygroscope, A Responsive Pavillion designed by Achim Menges and his collegues

< Source: Designboom, retrieved from https://www.designboom.com, 15 August 2018>

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[29] Kolarevic B., Parlac V.(Eds.), op. cit., p. 78

[30] Ibid

As an example of smart materials, Achim Menges, Steffen Reichert and Oliver David Crieg, who are professors in the University of Stuttgart, have developed a meteoro-sensitive pavillion named Hygroscope (Figure 3.5.) Hygroscope utilizes the intrinsic charactheristics of wood to produce an actuated response when exposed to different levels of humidity in the air.[31]

3.1.2. Types of Architectural Dynamism

As mentioned before, activation forces lead to dynamic movements in an environment. According to the science of dynamics, the forces cause various movement types: one dimensional movement, movement in two dimensions, periodic movement, circular movement, vibration, or oscillatory movement of objects.[32] During the evaluation of dynamic movements in the concept of architecture, the most important point is the spatial effection capacity of them on users and buildings. Hence, architectural dynamism, which causes the movement of architectural environment, could be examined into three sub-topics according to their size level of change and movability:

1. Spatial Dynamism (Macro-Level Dynamism)

2. Architectural Components Dynamism (Micro-Level Dynamism)

3. Nanotechnology-Based Dynamism(Nano-Level Dynamism)

1. Spatial Dynamism (Macro-Level Dynamism): Spatial Dynamism based on spatial movements, which can result in the differentiation of the overall shape or spatial configurations. It is mostly based on the movement of basic mechanisms around an axis. [33]

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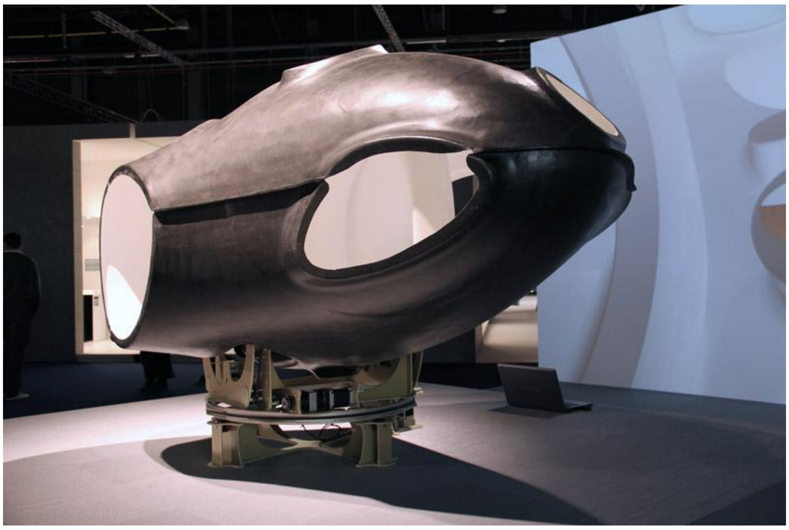
[31] Kolarevic B., Parlac V.(Eds.), op. cit., p. 82

[32] Elkhayat Y.O., (2014), op. cit., p. 2

[33] Megahed N.A., op. cit., p.6

(1)



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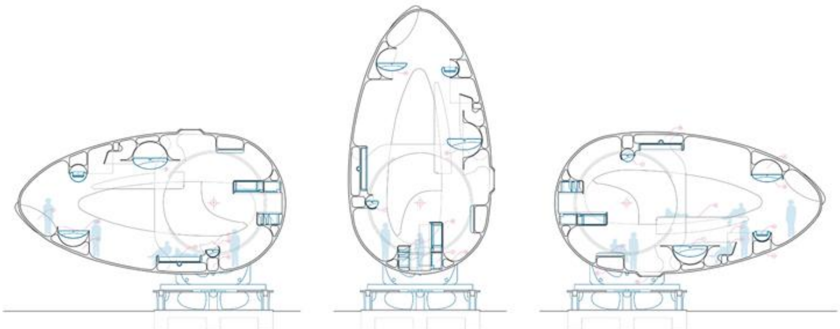

Figure 3.6. Greg Lynn's RV(Room Vehicle)

< Source: Designboom, retrieved from https://www.designboom.com/architecture/greg-lynn-rv-prototype-house/, 15 August 2018>

As shown in the example of Room Vehicle as a Prototype House (Figure 3.6.), which is designed by Greg Lynn, has a small footprint of 60 m^2 but it has a 150 m2 usable space area due to the ability of rotating around an axis. [34] Therefore, the architectural space could gain flexibility with rotation and increase the potential use of a space while one wall and ceiling is becoming floor surface by rotating.

2.Architectural Elements Dynamism (Micro-Level Dynamism): It is based on movement, transformation or formal deformation of architectural elements. As shown in Figure 3.7., architectural elements could move, fold, slide, expand or transform ing both size and shape with the help of pneumatic, chemical, magnetic, natural, or mechanical means.[35] Most of the transformations and deformations of the elements are realized physically rather than chemically.

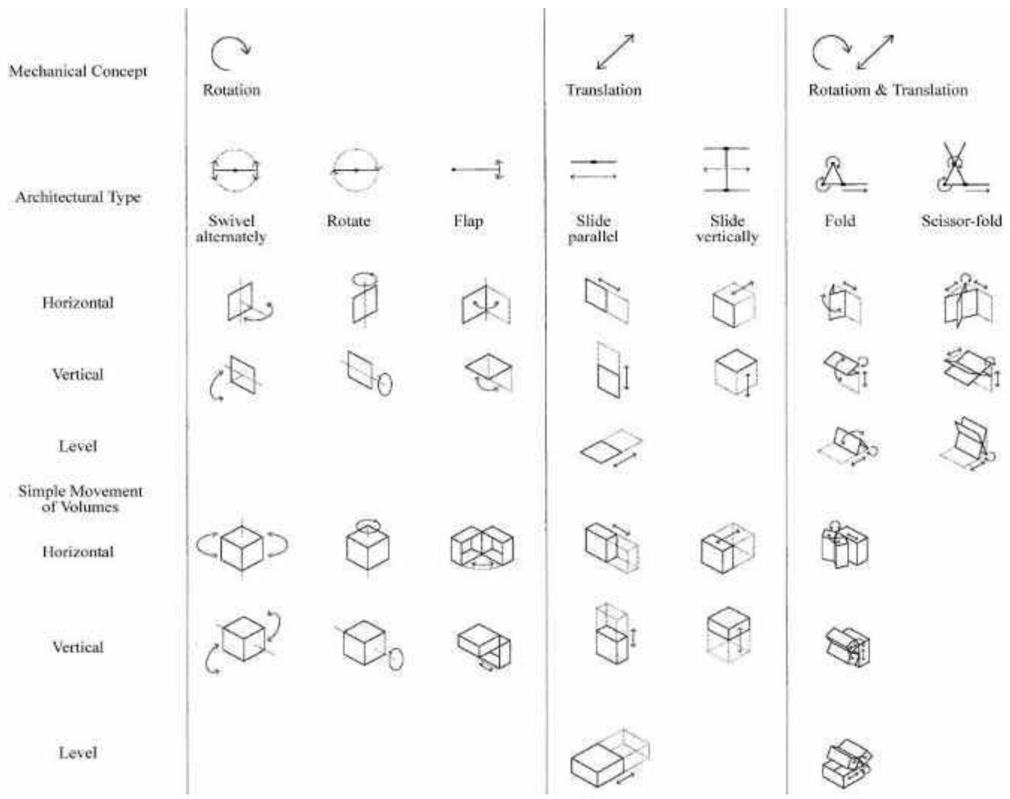

Figure 3.7. Mechanical Dynamism of Architectural Components

< Source: Youssef Osama Elkhayat, (2014), Interactive Movement in Kinetic Architecture, Faculty of Engineering, Tanta University >

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[34] Kolarevic B., Parlac V.(Eds.), op. cit., p. 5

[35] Megahed N.A., op. cit., p.7

Mechanical dynamic movements are applied in architecture generally with basic types of movement: rotation, translation or the combination of the two.[36] This type of movement is realized around the axis provided by connected hinges and joints.

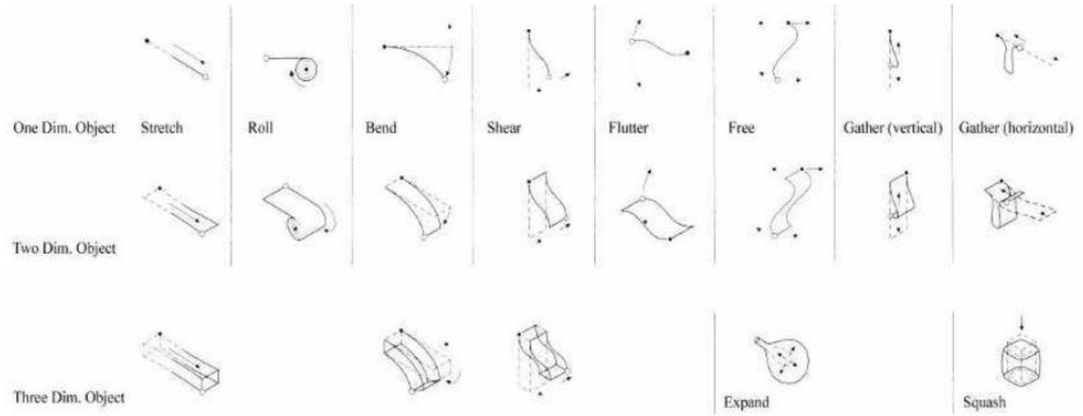

Figure 3.8. Deformative Dynamism of Architectural Elements

< Source: Youssef Osama Elkhayat, (2014), Interactive Movement in Kinetic Architecture, Faculty of Engineering, Tanta University >

Furthermore, as shown in Figure 3.8., deformative dynamism of architectural elements depends on the spesific material properties and combinations of the materials that are flexible and soft-form architectural elements, which could be able to deform under force. [37]

[36] Elkhayat Y.O., (2014), op. cit., p. 4

[37] Elkhayat Y.O., (2014), op. cit., p. 5

Figure 3.9. Architectural Elements Dynamism, Kinetic Façade, The Flare by Staab Architects

< Source: Demagazine, retrieved from http://www.demagazine.co.uk, 17 August 2018>

As an example of architectural elements dynamism, The Flare has a dynamic façade like a dynamic membrane, which consists of several tiltable metal flakes individually controlled by pneumatic cylinders. (Figure 3.9.) Each of the flakes moves and reflects the sunlight when in vertical position as a light pixel. When the flake is tilted downwards, it can provide shade from the sunlight while appearing as a dark pixel.

3.Nanotechnology-Based Dynamism(Nano-Level Dynamism): It contains material-based shape differentiations by smart materials at moleculer level. Transformation or deformation of architectural components depend on spesific molecular properties of materials, which can easily change with environmental effects such as heat, humidity and light.

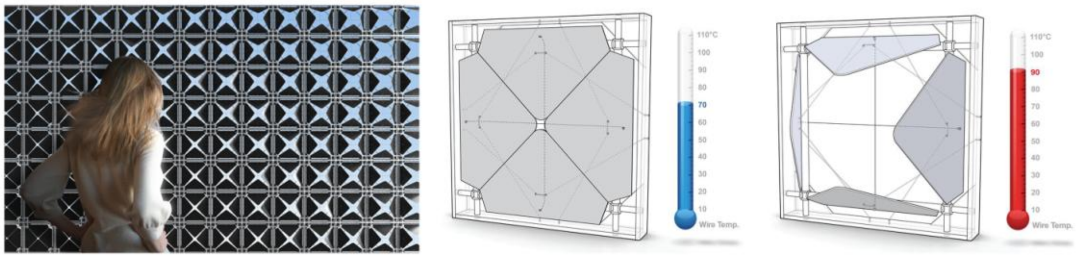

Figure 3.10. Nanotechnology-Based Dynamism, Shape Memory Alloy Panel System, A Student Project from MIT

< Source: Digital Fabrication Central of MIT University, retrieved from http://fab.cba.mit.edu, 20 August 2018>

As an example of Nanotechnology-Based Dynamism (Figure 3.10.), the Shape Memory Alloy Panel System is a heat sensitive façade system from a student project in MIT. The façade system consists of many calibrated Shape Memory Alloy wires acting as a sensor, processing device and actuator all in one according to heat changes.

3.1.3. Dynamism of Architectural Components

Dynamic movement of architectural components is very related with their role of in architectural environment, their internal physical and chemical properties and also relationships with the other architectural elements.

Considering the role of architectural components, dynamic transformation of architectural components could be examined according to their responsibilities in an environment. Architectural space could be realized with building components classified as follows:

1.Structural building components

2.Non-structural building components

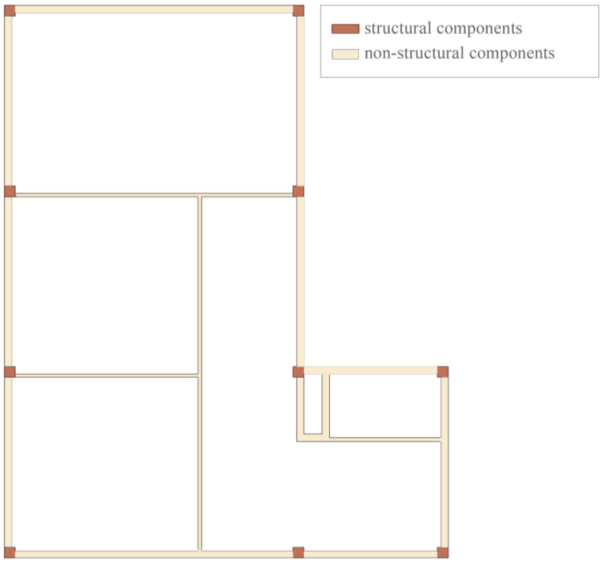

Figure 3.11. Structural and non-structural components of a building

While structural components are carrying the main loads of a building or construction, non-structural components enable creation of enclosed, semi-closed or borders of the space of a building (Figure 3.11)

3.1.3.1. Dynamism of Structural Components

The transformation of structural components is harder than non-structural ones due to the responsibility of carrying and transfering the main load. Structural components could be defined with their spesific properties: being soft-form or rigid-form buildings or structures.

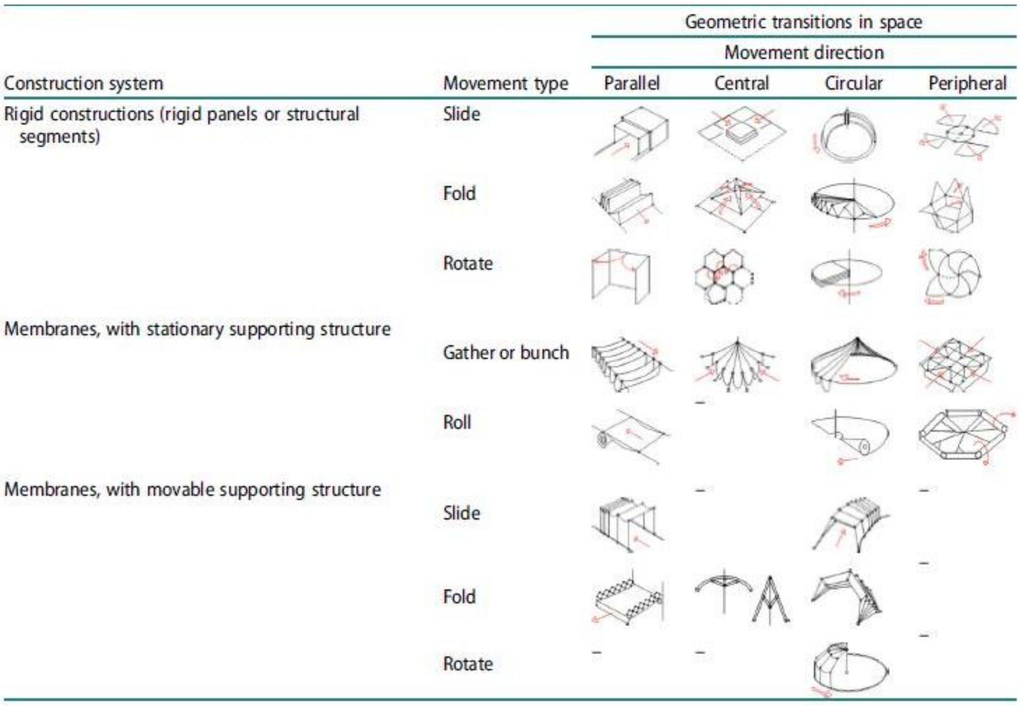

Figure 3.12. Transformation of architectural components, based on the drawings of Friedemann Kugel (Werner, 2013)

< <u>Source:</u> Naglaa Ali Megahed, (2017),Understanding kinetic architecture: typology, classification, and design strategy, Architectural Engineering and Design Management, 2017 Vol. 13>

As shown in Figure 3.12., while transformation mechanism of soft-form buildings made by membrane structures or cable-net pneumatic structures, transformation mechanism of rigid-form buildings made by rigid materials connected by joints and capable of deploying, folding, rotating, sliding and expanding.[38]

To obtain a transformable structure, the transformation mechanism of a structure should be well-designed. According to Chuck Hoberman,who is an architect studied on transformable structures, motion is not merely about physical quantity, it is about the relationships of change; the transformation mechanism is an embodied system of relationships.[39]

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38 Kirkegaard, P., Sørensen, J. (2009, September 28–October 2). Robustness analysis of kinetic structures. In A. Domingo, & C. Lazaro (Eds.), Proceedings of the international association for shell and spatial structures (IASS). Spain: Universidad Politecnica de Valencia.

39 Kolarevic B., Parlac V.(Eds.), op. cit., p. 109

Figure 3.13. In 1994, Iris Dome is designed by Hoberman with angulated scissors mechanism

< Source: Erich Bloom Design, retrieved from http://specialstructures.net, 15 August 2018>

As en example, Hoberman used angulated scissors to produce different motion paths of structure named Iris Dome. Kinetic mechanism of the structure is provided by multiple prototype reiterations over time as shown in Figure 3.13 and Figure 3.14.

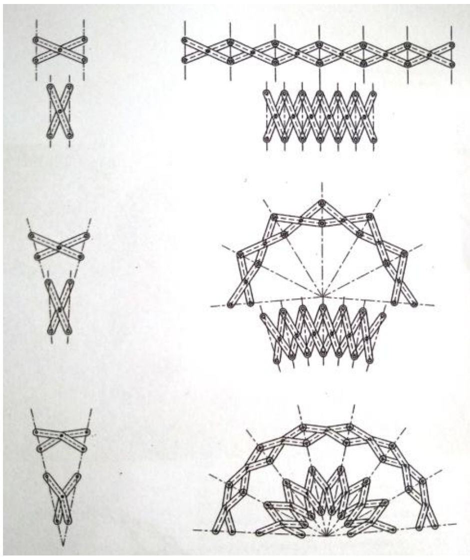

Figure 3.14. Angulated Scissors of Hoberman

< Source: Andrzej Zarzycki, Considering Physicality in Digital Models, New Jersey Institute of Technology, USA >

Following this logic, many different type of transformable structures could be evaluated. In New Jersey Institute of Technology, students tried to undestand the logic of Hoberman's sphere and created new form of structures. (Figure 3.15.)

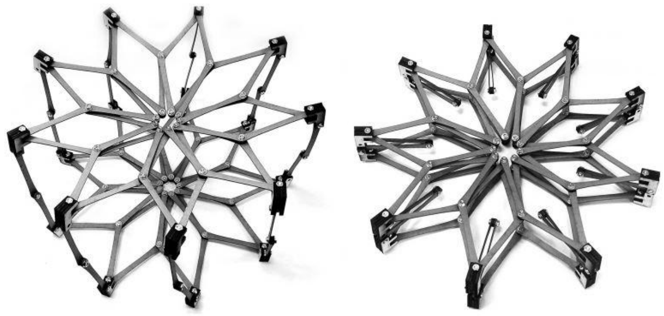

Figure 3.15. Student's Work

< Source: Andrzej Zarzycki, Considering Physicality in Digital Models, New Jersey Institute of Technology, USA >

Another work of students was on the purpose of investigating the kinetic behavior mechanism of a structure inspired by Theo Jansen's kinetic sculptures, which mimics skeletal systems (Figure 3.16).

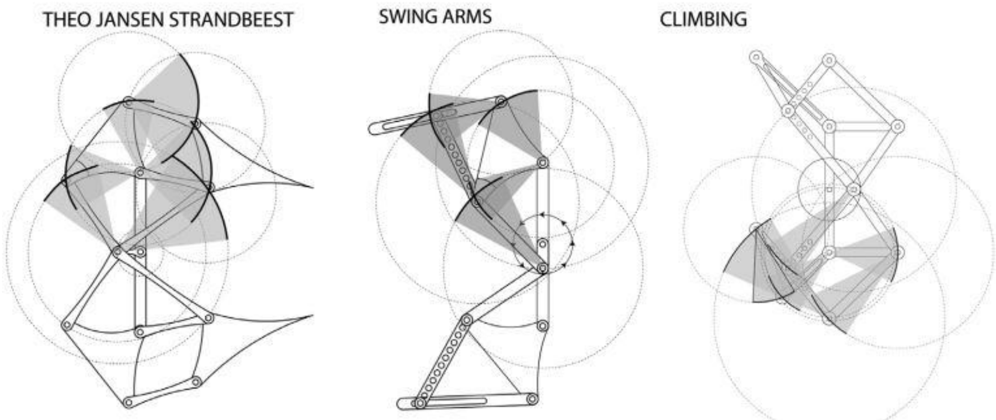

Figure 3.16. Student's Work

< Source: Andrzej Zarzycki, Considering Physicality in Digital Models, New Jersey Institute of Technology, USA >

In 2014, after trying to explore the variety of spinning shapes and forms, Hoberman proposed Morph (Figure 3.17), which is a model can change shape from a cube into a sphere. The sphere contains of an array of customized elements which can rotate synchronously on its own individual axis, thus it can change shape by rotating.

Figure 3.17. The Morph, Hoberman

< Source: Hoberman Design, retrieved from www.hoberman.com, 13 August 2018>

Recently, in architectural environment, innovative insight on exploratory mechanisms and materials rather than constant prototyping of components and their relationships have gained more importance. These innovations can open the way to the usage of new types of structural elements in architectural environments.

As an example of innovative material and relationships, researchers from Harvard University developed a new framework to design reconfigurable mechanical metamaterials in 2017, which has properties and functionalities that cannot be exhibited by conventional materials as shown in Figure 3.18. [40] New classes of these metamaterials could exhibit exotic functionalities in response to mechanical, motor-based forces, for guiding motion to transform pattern and shape. [41]

[40] Bertoldi K., Vitelli V., Christensen J., Hecke M., (2017), Flexible mechanical metamaterials

[41] Ibid

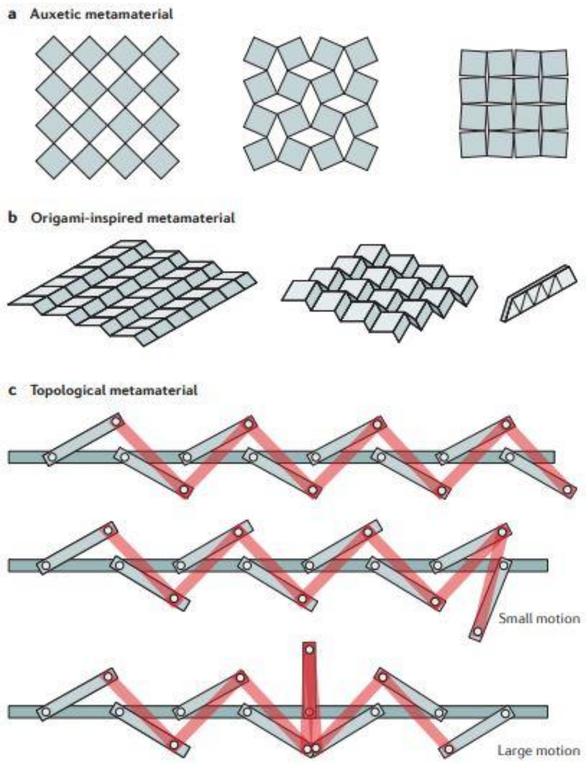

Figure 3.18. Different types of mechanism-based metamaterials

< Source: Katia Bertoldi, Vincenzo Vitelli, Johan Christensen and Martin van Hecke, (2017), Flexible mechanical metamaterials >

Following this research, researchers, in 2017 again, developed a structure which contains prismatic geometries with the properties of structural diversity and foldability guided by numerical analysis and physical prototypes, for enhancing the functionality of spatial architecture. The structure has the ability of reconfigurability with rigid plates and elastic hinges, which are identified with their internal rearrangements (Figure 3.19.). [42]

[42] Overvelde J.T.B., Weaver J.C., Hoberman C., Bertoldi K., (2017), Rational design of reconfigurable prismatic architected materials

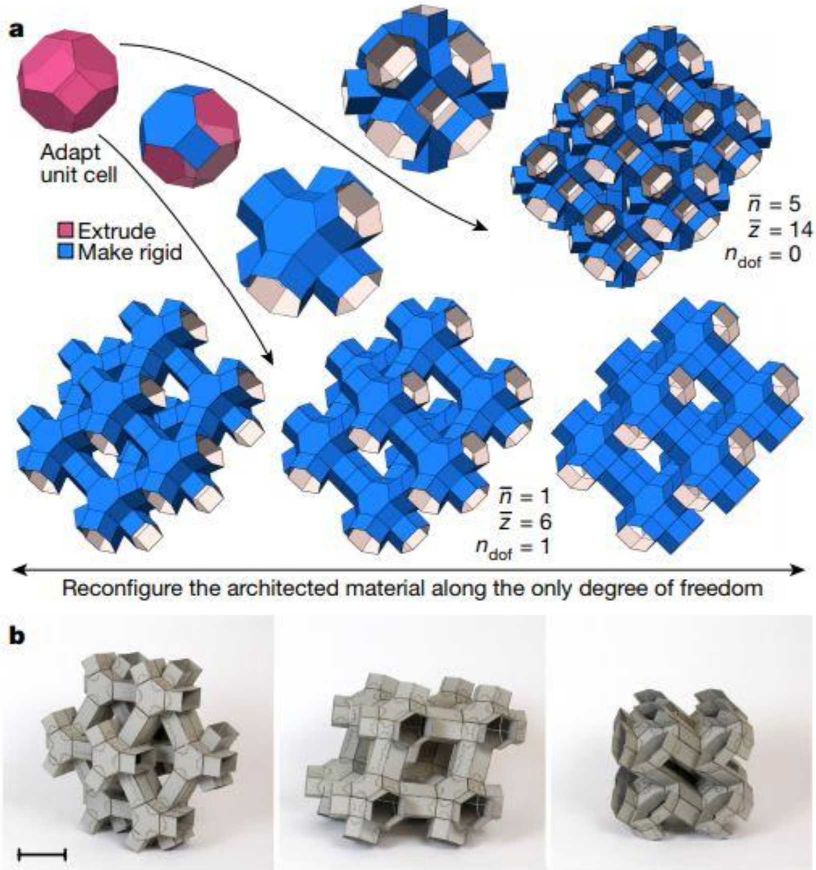

Figure 3.19. Reconfigurable Meta-materials

< Source: Johannes T. B. Overvelde , James C. Weaver, Chuck Hoberman & Katia Bertoldi1, (2017), Rational design of reconfigurable prismatic architected materials >

To conclude, with the help of fabrication technologies, it is possible to produce different types of architectural components, even metamaterials, with unprecedented transformation properties including their internal mechnisms of reconfigurability for spatial architecture.

3.1.3.2. Dynamism of Non-Structural Components

Non-structural components of an environment covers mainly interior and also exterior walls due to the fact that their main responsibility is defining borders of a space. Exterior and interior walls could be identified as skin of a building as they are the parts of a building interacting with the environment. For an "alive" building, the building interior and exterior skin should act as a living part of the building while being its "skin" not merely as a metaphoric meaning.[43]

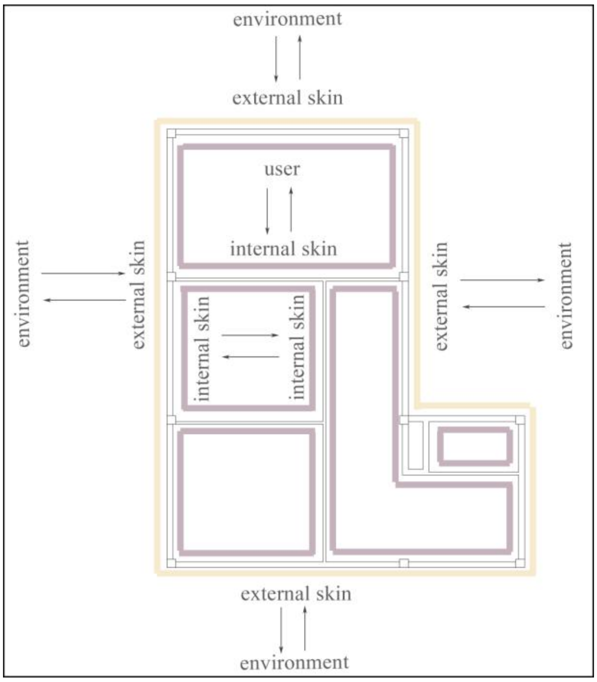

Figure 3.20. Internal-External Skin of a Building

While external skin of a building is interacting with environmental values such as heat, temperature, humidity, environmental buildings and the city, internal skin of a building is interacting with users and its own internal configurations (Figure 3.20.). Hence, dynamism of non-structural components could be evaluated according to their interaction results.

The external skin of a building (the external surface of a building) encounters different performance values of the temperature, light, air quality and wind, season by season even hour by hour cyclically. While external skin of a building is encountering these ever-changing values, the architects and users are trying to keep internal skin of a building at the same performance of the temperature, light, air quality and wind in the beneficial way of user's thermal comfort. This goal requires high-level energy consumption. To reduce energy consumption and the problems of

[43] Kolarevic B., Parlac V.(Eds.), op. cit., p. 70

the commonly used glazed façade lead the architects and engineers to begin studying dynamic performative skins. [44] The desire of performance control of skin of the building first lead to the evaluation of "dynamic wall". In 1981, Mike Davies proposed a "polyvalent wall"(Figure 3.21.) [45] as a dynamic intelligent wall, which is a wall for all seasons. [46] The wall could control the flow of energy from exterior to interior containing multifunctional layers. [47]

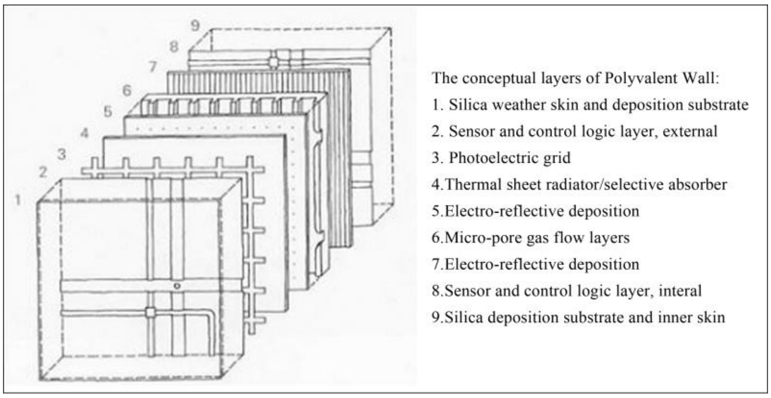

Figure 3.21. Polyvalent Wall, (1981), Mike Davies

< Source: Osman Ataman, John Rogers, (2006),Toward New Wall Systems: Lighter, Stronger, Versatile, University of Illinois at Urbana Champaign, School of Architecture >

Then in the beginning of 1990s, the concept of dynamic and adaptive façade appeared with the idea of when the ratio of light and temperature is changing, the internal and external skin of a building can also change as a dynamic environment while adapting the performative values. The concept of dynamic and adaptive façade, which follows the changing external world, could provide maximum benefit from the sun as well as providing energy and economy saving by regulating the conditions of its internal and external skins in its own organization. The studies on performance

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[44] Kolarevic B., Parlac V.(Eds.), op. cit., p. 60

[45] Ibid

[46] Ataman O., Rogers J., (2006), Toward New Wall Systems: Lighter, Stronger, Versatile, University of Illinois at Urbana Champaign, School of Architecture

[47] Ibid

issues of the dynamic skin of a building continued at different levels of dynamism. On one hand, architects have been studied on the performative values of material-level structures and elements on the façade, on the other hand, they have been studied on the design strategies of dynamic energy efficiency façade design of the building.

As shown in Figure 3.22., The Sharifi-ha House in Tehran, Iran, designed by NextOffice, is an example of macro level dynamic façade, which features motorized rooms that pivot up to 90 degrees to face entirely in or out to adapt to changing seasons or functional scenarios.[48]

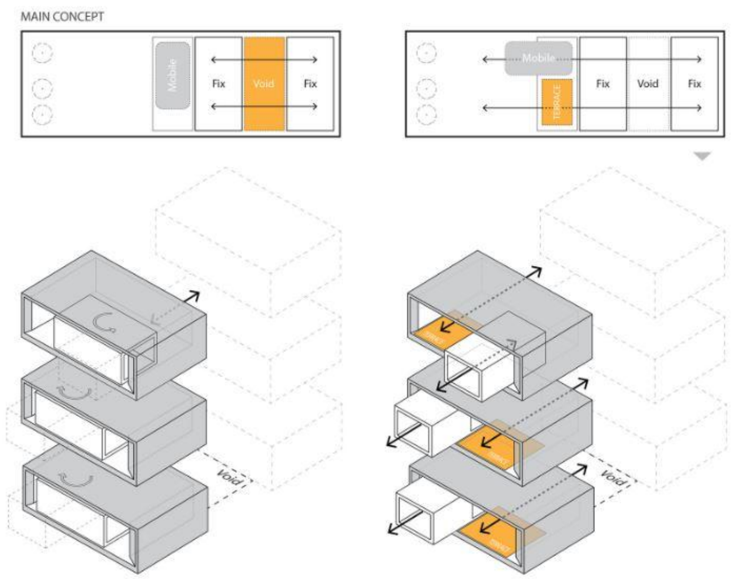

Figure 3.22. Sharifi-Ha House, Dynamic Façade

<Source: Archdaily, retrieved from http://www.archdaily.com/ , 20 August 2018 >

While dynamic interactions between environment and the building is leading to the dynamism of external skin of a building, both interactions between environment and the building (it means building internal configurations and building) and also dynamic interactions between user and building lead to the dynamism of internal skin of a building. For this reason, while architects examined the external dynamism

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[48] Orhon A.V., (2016), Adaptive Building Shells, p 558

of a building mostly in the perspective of environment- building interactions, internal dynamism of a building mostly in the perspective of human-building interactions mainly on functional flexibility of a space. Gerritt Rietveld, in 1924, built Schröder House (Figure 3.23.) with its internal adaptive space, which can be used as an open space or subdivided into the separate rooms, which have different functionality, with the help of sliding and revolving partition walls.[49]

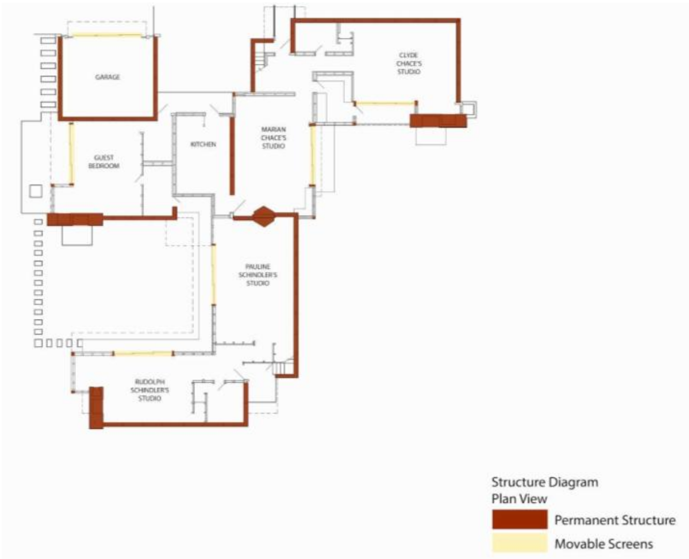

Figure 3.23. Schröder House Plan

<Source: Inhabitat, retrieved from http://www.inhabitat.com/, 20 August 2018>

[49] Kolarevic B., Parlac V.(Eds.), op. cit., p. 11

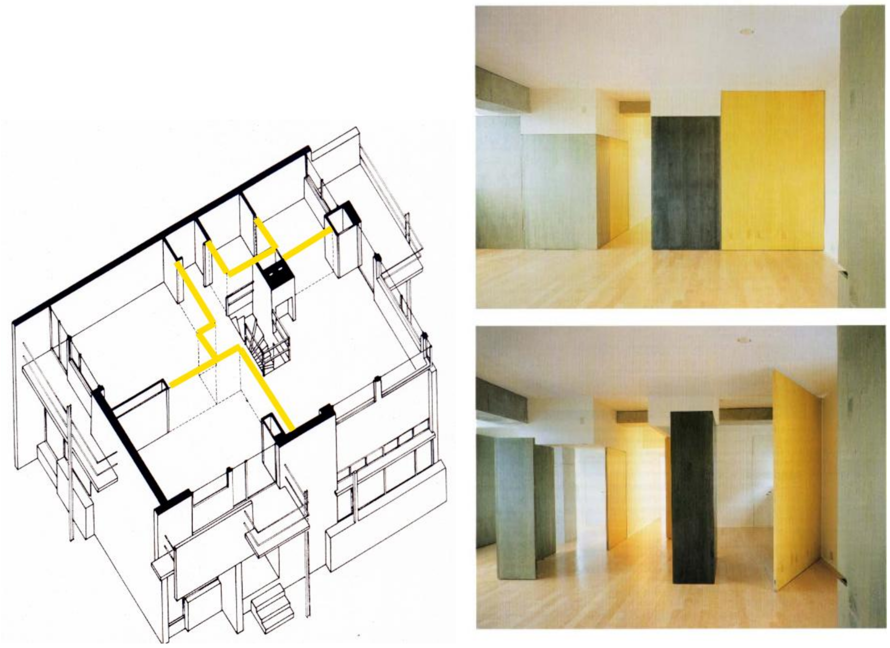

Figure 3.24. Hinged Space Housing, Steven Holl, 1991, Fukuoka, Japan

< Source: Virginia University, retrieved from http://faculty.virginia.edu/ , 20 August 2018 >

In a similar manner, Steven Holl designed Hinged Space Housing (Figure 3.24.), constructed in 1991 in Japan. This apartment has hinged adaptive wall system for creating an adaptive functional space, which could change daily or on a larger time scale as family size changes.

CHAPTER 4

INTELLIGENCE OF ARCHITECTURAL ENVIRONMENT

In this chapter, the affects of the advances in the field of artificial intelligence to architecture is declared and how to create an intelligent space is discovered.

4.1. The Intelligence of Architectural Environment

Over the centuries, people tend to attribute their own characteristics to other living organisms and lifeless assets. The idea of creating an intelligent asset, which could be able to think like a human, leads to discover the topic of "Artificial Intelligence" that is a field of studying the computation of intelligent agents, their behaviours and intelligent systems.[50] With the help of artificial intelligence, an agent, which can be a living organism or lifeless asset, could gain memory and a logical system to be an intelligent agent.

In 1960s, the term "Intelligence" appeared in the field of architecture with the evaluation of an architectural space as an intelligent asset. Groups like Archigram, a group of London architects, carried the term of "Intelligence" to the architectural environment so that spaces could be changeable through computation and technology in order to achieve user's wishes and needs.[51] Architects of Archigram proposed intelligent and changeable environment examples such as Living Pod and Walking City. As an example, David Greene proposed Living Pod that is a capsule house described as teaching and working machine, as shown in Figure 4.1.

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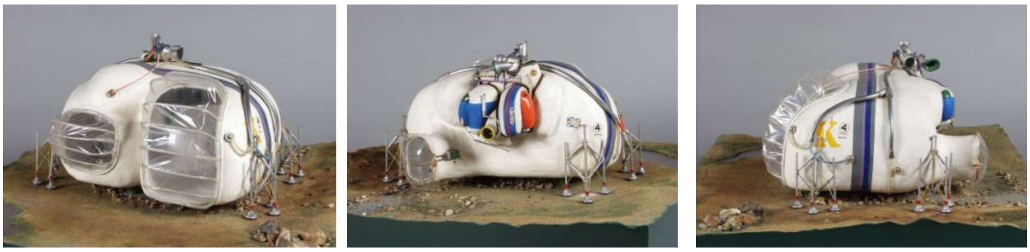
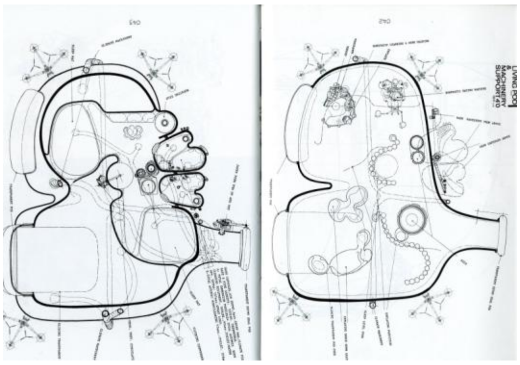
[50] Poole D.L., Mackworth A.K., (2010), Foundations of Computational Agents

[51] Megahed N.A., op. cit., p.2

(1) 

(2) 

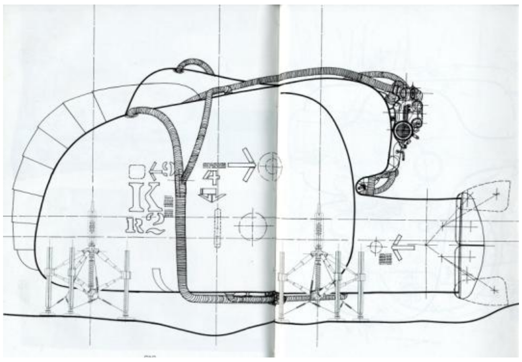
(3) 

Figure 4.1. David Greene, Living Pod, Archigram, 1966

< Source: Hidden Architecture, retrieved from http://www.hiddenarchitecture.net/2016/06/living-pod.html, 25 August 2018>

On one hand the context of "intelligence" in architectural environment had a position in the way of reponsiveness and interactivity thanks to the Archigram architects, on the other hand, after the energy crisis in 1973 and with the developments in the field of artificial intelligence in 1980s, "intelligence" of architectural environment could reach another position in the way of energy saving and consumption, as well. Hence, the evaluation of "Intelligence" in architectural environment could be mainly examined following these two ways; intelligence of interactive environment and intelligence of performance-based intelligent environment. While "Intelligence" of interactive architecture progressed by applying cybernetics to build an intelligent user-adaptive or environment-adaptive architecture, intelligence of intelligent and performative architecture progressed in the way of integrated control mechanisms for energy usages.

To conclude, today, the main objective of each type of dynamic architecture is to make buildings smart and dynamic in accordance with its own intelligence, which could enable them to have the ability of being sensitive, adaptive, and responsive to stimuli. By increasing the branches of dynamic architecture, the evaluation of "intelligence" in architectural environment have been diversified according to each branch of dynamic architecture. Although each of them evaluates the intelligence according to its own way, "Intelligence" of dynamic architecture has been improving for years following the developments in the field of computation, electronical engineering and structural engineering. Besides, following the latest improvements in artificial intelligence could develop the intelligence of architectural environment into the more and more positive way.

4.1.1. History of Artificial Intelligence and the Reflections of AI on Architecture

In a period, each scientific development improves almost in the light of parallel ideas due to the fact that the scientific background is ready for the emergence of the invention. Both affection of different disciplines to each other and preparation of one invention of the other one's ground in the same disciplinary framework could be reasons of the inventions. Hegel, who is a German philosopher, claims that with the term of "Zeitgeist", which means that the spirit or mood of a particular period of history as shown by the ideas and beliefs of the time.[52] As mentioned before, dynamic architecture is affected by the discipline of artificial intelligence in the historical process. Hence, evaluation of the developments in the history of artificial intelligence could be beneficial to better understand the background ideas of dynamic

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[52] Oxford English Dictionary, (2018, August 20), retrieved from https://en.oxforddictionaries.com/definition/zeitgeist

architectural improvements and also following the new developments in the artificial intelligence discipline could lead to new improvements in the dynamic architectural environments as discussed before.

The logical background of Artificial Intelligence is based on the abstraction of decision-making process of a human. Firstly, decision-making process of a human is seen as a symbolic reasoning process after following the ideas of Hobbes, who is an English Philosopher prominent as “Grandfather of AI”. He put up the argument that creation of thoughts of a human is a symbolic reasoning process. With the development of computers, symbolic reasoning formed the basis of computation.

In 1936, Alan Turing proposed an abstract machine: Turing Machine as a computation model. He pointed out the essence of the theory "thinking is computing". [53] Afterwards, in 1950, he compared the human and the machine intelligence with Turing test in his paper named ‘Computing machinery and intelligence’.[54] The Turing test clearly emphasizes that the machine’s intelligent behavior is more definitive and certain rather than human behavior. Ill-definition, uncertainty and multiple objectives are primary characteristics of human decision-making processes in contrast to a machine’s behavior.

For the first time, in 1956, McCarthy used the terminology of "Artificial Intelligence", which is based on symbol processing mechanism.[55] After that, in 1961, cybernetics [56] appeared in the field of engineering and mathematics as an academic discipline that deals with the matter of control and correspondence in a system like

[53] He, X., Xu, S., (2007), Process Neural Networks, Zhejiiang University, China

[54] Lu X., Clements-Croome D., Viljanen M., Past, present and future mathematical models for buildings focus on Intelligent Buildings (Part 1)

[55] Ibid

[56] Wiener N., (1961), Cybernetics: or Control and Communication in the animal and the machine

an organism or a machine.[57] Following the development of cybernetics, James Graham Ballard, who is a British novelist, described a machine-like house "psychotropic house" in one of his stories in 1962. [58] According to this story, a wife killed her husband in a house, which could remember the crime and could use the acquired information of crime for reconstituting its conditions again in a same way. To have same conditions again provide a psychoanalysis under hypnose for healing a patient while reconstructing his trauma.

Designing 'systems' rather than depicting static images[59] appeared in the field of architecture in 1964, after a seminal book on the participatory planning methods named "Architecture without Architects."[60] Then, Archigram architects began to propose innovative dynamic architecture examples. In 1964, Ron Herron, who is a notable English Archigram Architect, proposed a hypothetical project "Walking City" (Figure 4.2.) , in which the buildings are imagined as giant mobile and transformable robotic structures. [61] As mentioned above David Greene proposed the Living Pod. Furthermore, with Cedric Price's Fun Palace and Nicholas Negroponte's Soft Architecture Machines, several concepts, which emphasize the architecture operational capacity and the architect's role as a system designer, are developed in the 1960s and 1970s.

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[57] Hotta K., Hotta A. (2016), The Implementation of Programmable Architecture: Wireless Interaction with Dynamic Structure, Living Systems and Micro-Utopias: Towards Continuous Designing, Proceedings of the 21st International Conference of the Association for Computer-Aided Architectural Design Research in Asia CAADRIA 2016, 291–299, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

[58] Kolarevic B., Parlac V.(Eds.), op. cit., p. 3

[59] Ibid

[60] Rudofsky, B., (1964), Architecture without Architects, Univ of New Mexico Press, Mexico.

[61] Kolarevic B., Parlac V.(Eds.), op. cit., p. 4

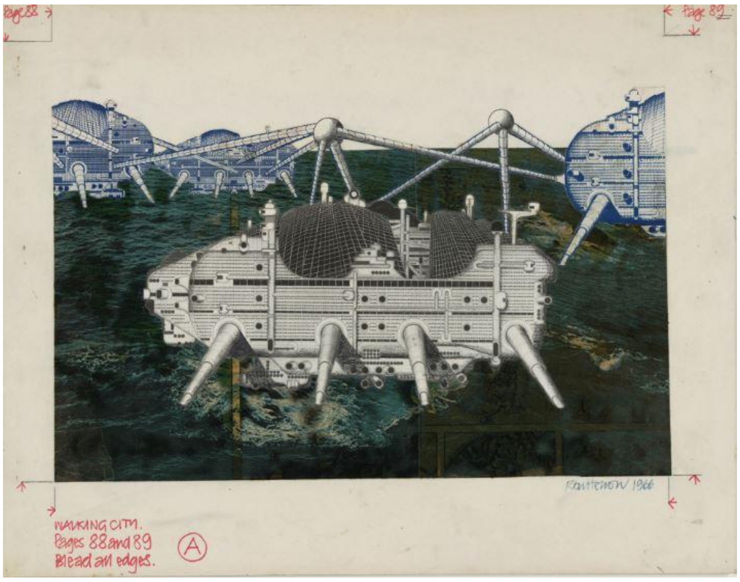

Figure 4.2. Ron Herron, Walking City, Archigram, 1964

< Source: MOMA, retrieved from https://www.moma.org/collection/works/814, 14 July 2018>

In 1972, Charles Eastman proposed automated control systems for controlling the responses of building in the concept of "adaptive-conditional architecture". This automated control system use feedbacks from the environment and the user to self-adjust in a dynamic stability.[62] The proposal of Eastman led the architects and researchers exploring the processes of "intelligence" of an architectural environment as a two-way relationship between user and space or environment and space. [63]Approximately at the same time (1975), Nicholas Negroponte proposed machine assisted/controlled environments, which can be produced with integrated computers into the buildings so that they can perform better as an evolving mechanism like a computer.[64] Negroponte claimed that the computing power, which is integrated to the buildings, could be able to turn buildings into "architecture machines".[65] Researchs on developing the control system mechanisms integrated to the building gained speed

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[62] Kolarevic B., Parlac V.(Eds.), op. cit., p. 4

[63] Kolarevic B., Parlac V.(Eds.), op. cit., p. 178

[64] Kolarevic B., Parlac V.(Eds.), op. cit., p. 4

[65] Fox M., Kemp M., (2009), Interactive Architecture, p. 3

after the energy crisis in 1973, and then building research on energy demands, passive design, environmental comfort and response of the control have began to apply with single function dedicated systems after 1980s.[66]

After 1980s, the application and evaluation of "intelligence" to architecture came to parting of the ways for some reasons. Although there appeared many different ways of applying intelligent behavior to the architectural enviroment, two main application of intelligence to the environment attract the attention significantly: on the way of interactivity (interactive architecture) or on the way of intelligent performance control systems (intelligent architecture).

According to one perspective of historical process research on Intelligent Architecture can be divided into three main sub-headlines; first generation, second and third generation of intelligent architecture. First generation of intelligent building research began in 1980s with independent automatic sub-systems, which controls work HVAC, security systems, access, water, lifts and so on. The control systems operate independently of each other and are not connected. In 1990s, these control systems are began to connect to each other via a network. Advantage of this connection is providing a possibility of controlling them remotely and facilitating the control of them from one or more central points. And then, almost at the end of 1990s, the third generation of intelligent buildings appeared in the field of intelligent architecture with learning capability from environment and users. For the purpose of learning from environment with feedback loops and controlling the behaviors of itself to manage adaptation, the application of intelligent agent techniques(such as robotics) emerged in the field of intelligent architecture.[67] After 2015, the focal point of intelligent buildings shifted from Building Control Systems such as Bulding Automation Systems to adaptive control system mechanisms with advanced sensors. This development could bring into the buildings the ability of self-adaptivity.

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[66] Stephenson, D.G. and Mitalas, G.P., (1971), 'Calculation of heat conduction transfer functions for multilayer slabs', ASHRAE Transactions 77(2), 117–126

[67] Sharples S., Callaghan, V., Graham C., (1999). Multi-agent architecture for intelligent building sensing and control. Sensor Review - Sens Rev. 19. 135-140. 10.1108/02602289910266278.

On the other perspective of historical process, Interactive Architectural Research continued with focusing more on adaptive and responsive façades featured energy saving in 1990s and 2000s. Afterwards, in the wake of Negroponte, Michael Fox, who is a famous architect studies on dynamic structures, proposes that intelligence of an environment could be managed with kinetic architectural structures, which are controlled by a responsive in-direct control mechanism. The proposed control mechanism contains a central computer, whose program receives environmental inputs via sensors and then send optimal solution instructions to actuators for moving a single architectonic elements.[68] With the proposal of Michael Fox, at a point of view, he could manage to convene the historical processes of intelligent-performative and interactive architecture for creating an intelligent control system, which works through kinetic structures. Following the idea of Fox, the new interpretation of intelligence could be strengthen more and more by applying latest developments in the field of artificial intelligence.

When looking back at the field of AI, during the 1990s and 2000s, there were many studies newly emerging on the field of Machine Learning as a sub-set of artificial intelligence. Machine Learning (ML) algorithms could give the ability to autonomously learn from data and information to computers. Thus, with machine learning, computers can change and improve their algorithms by themselves. Moreover, ML algorithms could give the ability of optimization and probability to the computers more precise compared to the conventional algorithms. In the architectural context, ML is mostly used for the optimization of dynamic element behavior patterns. As shown in Figure 4.3., Lace Wall could be an example project of optimization of dynamic behaviors through ML algorithms. The project wall is constructed by 8-mm glass-fibre-reinforced plastic rods, textile cables and custom designed high-density polyethylene (HDPE) elements to join cables and rods together. The rods are bent and joined into discrete units stabilised by an internal 3D

[68] Yiannoudes S., (2016), Architecture and Adaptation: From Cybernetics to Tangible Computing, New York: Routledge

cable network. The internal cable-net gives the instructions for fitting each individual plastic rod to the overall desired macro-shape.[69]

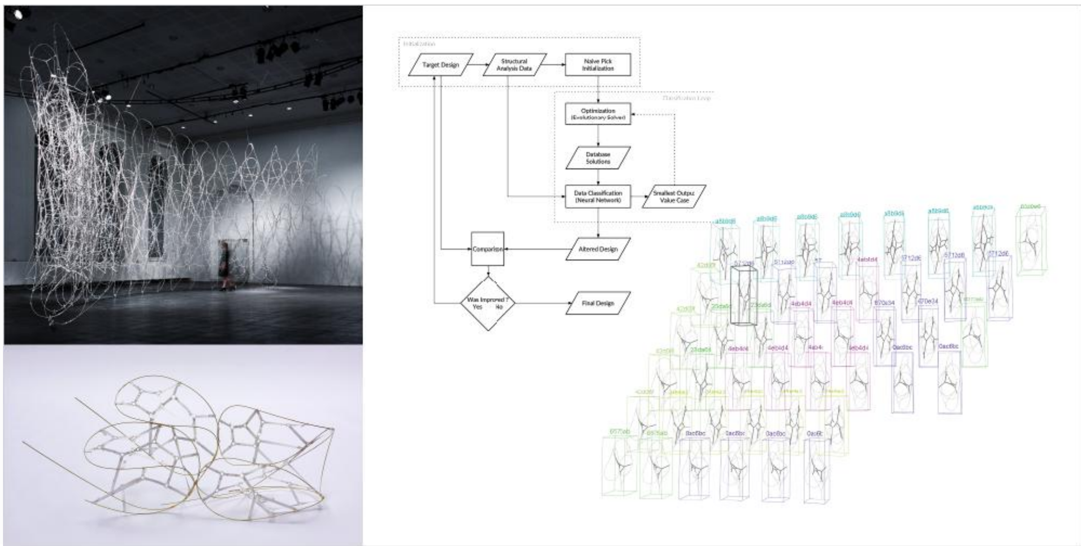

Figure 4.3. Lace Wall, 2016

<Source: KADK, retrieved from https://kadk.dk/case/lace-wall , 30 September 2018 >

Furthermore, in 2000s, the robotics field gained important progress in the framework of robot behaviors with swarm robotics. Swarm robotics is a multiple robot system, which is developed by computer scientists, based on swarm intelligence inspired by animal behavioral patterns. Through coordinated motion and self-assembly, these robots are able to efficiently perform cooperative tasks that cannot achieved by a single robot.[70] In the context of architecture, Swarm-Roof can be shown as an example of swarm robots project, which uses cooperative skill of swarm robots while reconfiguring its overall form according to changing circumstances. Swarm roof is a

[69] Tamke1 M., Nicholas P., Zwierzycki M., (2018), Machine learning for architectural design: Practices and infrastructure

[70] Yiannoudes S., op. cit. p.69

reconfigurable shading system consisted of robotic modules embedded in a roof structure (Figure 4.4.) [71]

Figure 4.4. Swarm Roof, 2009

< Source: Socrates Yiannoudes, 2016, Architecture and Adaptation, From Cybernetics to Tangible Computing>

In 2006, "Deep Learning" algorithms, which let computers to see and identify objects, texts and images, appeared in the field of machine learning. In 2011 Google developed deep learning neural networks for discovering and categorizing information, and in 2015 Facebook used deep learning algorithms for face detection. In 2015, Microsoft developed a system, which can manage to solve problems across multiple computers using a consistent, task-oriented interface. Deep learning has a big potential for intelligent spaces, and trends in machine learning computation and robotics could open up new opportunities for developing a new vision of a smart, interactive, and responsive architecture.[72]

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[71] K.Hotta, A.Hotta ,op. cit. p.294

Main Source: Lipson, 2000

[72] Pan C.A., Jeng T., op. cit. p.1

4.1.2. Construction of an Intelligent Space

Numerous researchers and architects have been using the term of intelligent space to refer to many types of structures, installations and buildings embedded with computational technology. In other words, an intelligent space means a computationally augmented space in general.

Applying intelligence to the architectural environment could be evaluated with two main headlines. On one hand "intelligence" is applied to the Interactive Architecture mostly partially through embedded computation to the partial elements and structures of a space. Embedded Computation refers to the electronic and computing devices that are embedded in current architectural elements or components for gathering information, processing it and then using the outputs to control the behavior of physical parts of architecture in the context of interactive architecture. Hence, it adresses embedded system which consists of the combination of sensor technology, interaction management with the help of computational process and control mechanisms, also actuator technology.

On the other hand, according to Intelligent Architecture, the design and construction of "intelligence", which could be defined as "ambient intelligence", is managed by the integration of computerized and automated intelligent systems to the whole building, while considering responsiveness and adaptiveness.

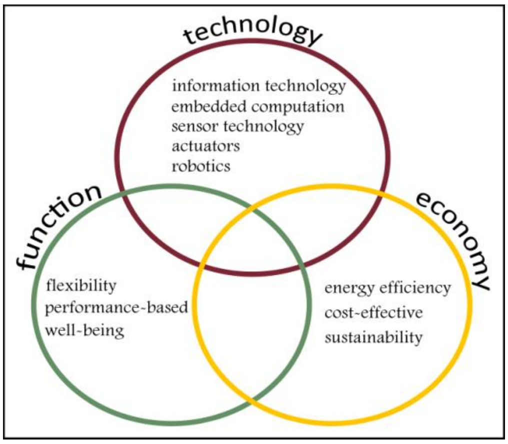

Figure 4.5. Three Essential Components of AmI

< Adapted from Huang Ambient Intelligence definition >

In intelligent architecture, inasmuch as promoting energy saving, cost-effective, sustainability and also creating a functional and healthy architectural environment for users, an ambient intelligence consists of intelligent systems, which cover the topic of robotics, embedded sensor technology, communication and information technology (Figure 4.5).[73] Hence, an ambient intelligence could be evaluated as a digital environment that proactively supports users daily lives in various perspectives.[74]

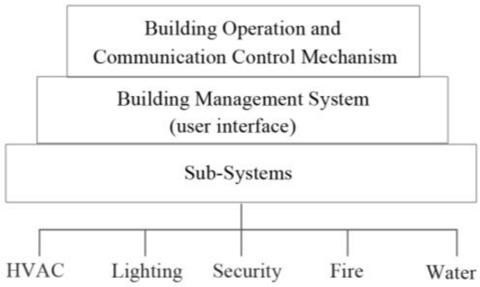

Figure 4.6. The Three levels of Intelligent Systems

Generally, an Ambient Intelligence(AmI) comprises three levels of system integration as shown in Figure 4.6. [75] The main control mechanism of building operations and management draws the general framework of building operation rules of systems and communication management systems. Building Management System could be defined as user interface, which controls and coordinates the sub-systems. Sub-systems are mainly called as Building Automation Systems (BAS)[76], which consider the energy performance of a building and the comfort of the users that could

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73 Clements-Croome D. J., (2013). Intelligent Buildings: Design, management and operation (Second ed.). London: ICE Publishing

74 Augusto J.C., (2007), Ambient Intelligence: the Confluence of Ubiquitous/ Pervasive Computing and Artificial Intelligence, Springer London, pp 213–234. Intelligent Computing Everywhere

75 Lu X., Clements-Croome D., Viljanen M., (2009), Past, present and future mathematical models for buildings, Intelligent Buildings International, 1:1, 23-38

76 Wang, S., (2010), Intelligent Buildings and Building Automation. New York: Spon Press.

be listed as visual comfort, thermal comfort and indoor air quality comfort in an environment.[77] They are the service systems such as heating system, ventilation and air-conditioning (HVAC), lighting, transportation and security system. Building Automation Systems can be evaluated within a fragmented operational framework[78] or with a system which consisted of many subsystems that are logically connected in various ways and joined to shape a complete system.[79]

As shown in Figure 4.7. , control and management of an intelligent system begins with field devices such as sensors and actuators, which are dispersed in buildings to control heating, ventilation, and air conditioning and so on. Then through wireless and wired communication technology, the information acquired from the sensors transfers to sub-controllers or main controller computer. Information flow through processed sub-control units can facilitate the performance of the system main control mechanism. After evaluation of information, the instruction coming from the main controller transfers back to the actuator tools.

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77 Dounis, A. I., Caraiscos, C., (2009), Advanced control systems engineering for energy and comfort management in a building environment-A review. Renewable and Sustainable Energy Reviews, 13(6-7), 1246-1261. doi: 10.1016/j.rser.2008.09.015

78 Prakash, P. (2013). Building automtaion for enhanced energy and operational efficiency. Texas: Texas Instruments

79 Wang, S., (2010), Intelligent Buildings and Building Automation. New York: Spon Press

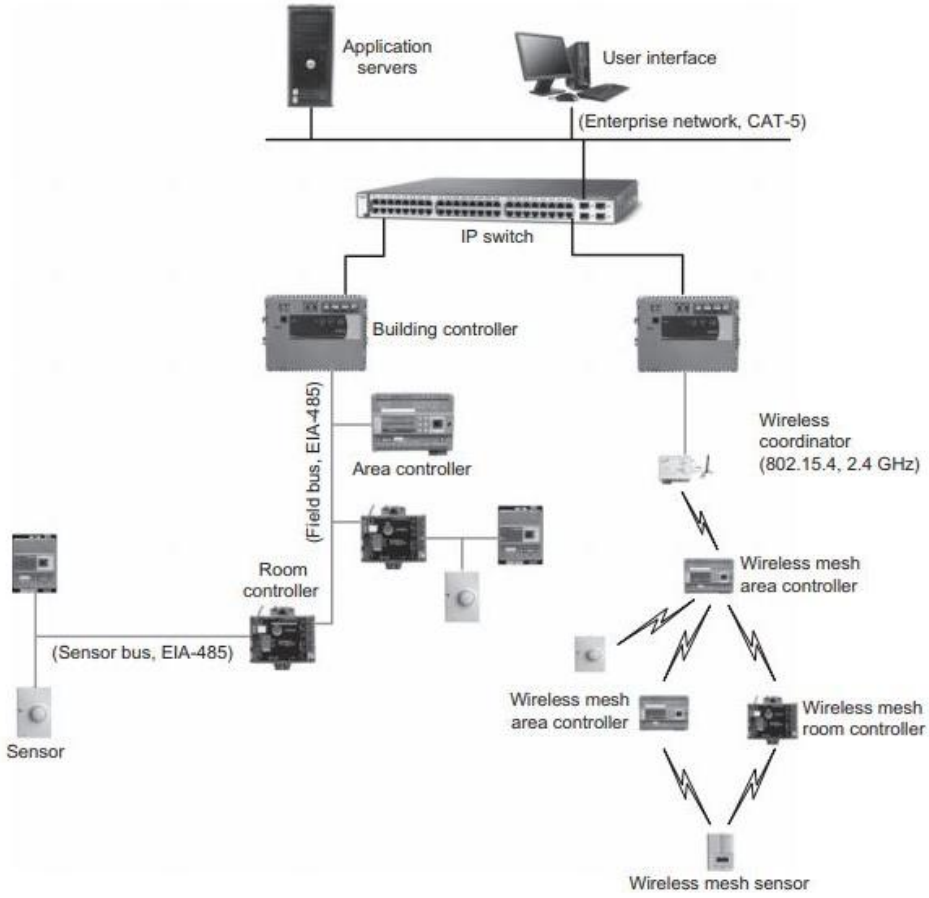

Figure 4.7. BAS wired and wireless controller types and networks

< Source: Jean-Philippe Vasseur Adam Dunkels, (2010), Interconnecting Smart Objects with IP: The Next Internet >

Firstly, in 2002, an interactive space is realized as an intelligent space with embedded systems integrated to the whole architectural environment like seen in intelligent architectural spaces. The ADA project was presented in Swiss National Exhibition. The embedded intelligent systems of ADA could be defined as an interactive infrastructure (Table 4.1.). ADA's interactive infrastructure, which is based on artificial neural networks and agent-based software components.

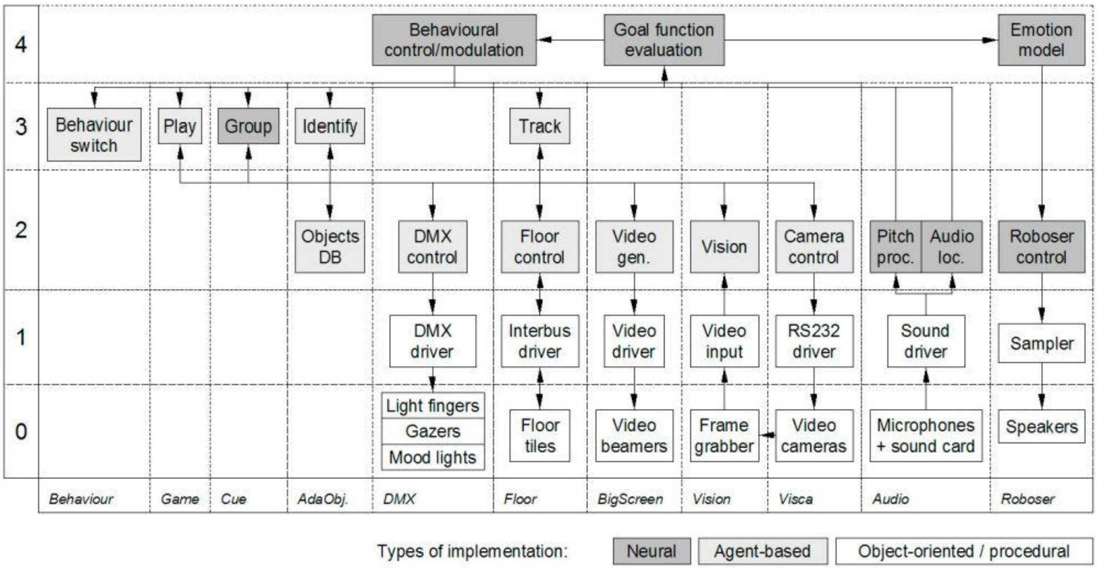

Table 4.1. Layer by layer ADA's Infrastructure

< Source: Eng K., Bäbler A., Bernardet U., Blanchard M., Costa M., Delbrück T., Douglas R. J., Hepp K., Klein D., Manzolli J., Mintz M., Roth F., Rutishauser U., Wassermann K., Whatley A. M., Wittmann A., Wyss R., Verschure P. F. M. J., Ada-Intelligent Space: An artificial creature for the Swiss Expo.02, Proceedings of the 2003 IEEE/RSJ International Conference on Robotics and Automation (ICRA 2003), Taipei, Taiwan, September 2003>

The whole system is composed conceptually according to the ADA-human interaction and its behavioral outputs are in real-time. As shown in Figure 4.8., ADA can interact with visitors while playing a game with them through its infrastructure. For the creation of this interactive space, a technical team, which consists of over 100 people, gathered from different professions such as architects, biological scientists, publicists, artists, engineers, scenographers and also on-site managers. [80] Due to having intelligent systems as its infrastructure for a whole architectural environment, from a point of view, this development could be evaluated as the convergence of two different intelligence approaches for architectural environment,

[80] Eng K., Bäbler A., Bernardet U., Blanchard M., Costa1 M., Delbrück T., Douglas R.J., Hepp K., Klein K., Manzolli J., Mintz M., Roth F., Rutishauser U., Wassermann K., Whatley A.M., Wittmann A., Wyss R., Verschure P.F.M.J., Ada-Intelligent Space: An artificial creature for the Swiss Expo.02, Proceedings of the 2003 IEEE/RSJ International Conference on Robotics and Automation (ICRA 2003), Taipei, Taiwan, September 2003

which are intelligence of intelligent architectural approach and intelligence of interactive architectural approach.

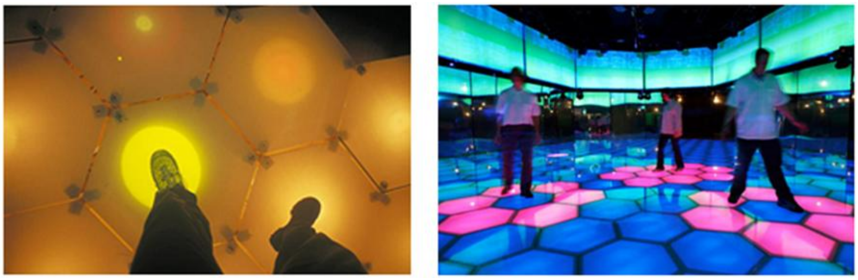

Figure 4.8. Skin of ADA

<<u>Source:</u> Interactive Architecture Lab, retrieved from http://www.interactivearchitecture.org/ada-the-inteligent-room.html, 20 August 2018>

Furthermore, in 2010, while the control mechanism of an AmI is constructed by intelligent systems as explained, the control mechanism of dynamic systems is developed by researchers from Massachustts Institute of Technology including Michael Fox through the article named "Intelligent Kinetic Systems". According to this article, the partial embedded kinetic elements of a building could also work together in cooperation as a control mechanism rather than being independent dynamic structures. They proposed the concepts of kinetic intelligent systems such as ubiquitous responsive in-direct control mechanism and heuristic, responsive in-direct control mechanism. According to ubiquitous responsive in-direct control mechanism, movement could be managed by a networked whole system, which is consisting of a series of autonomous computer controlled senso-motor (actuator) parts (and/or panels) acting together. This predictive, auto-responsive and adaptive system logic is based on the feedback loops coming from environmental inputs. [81] The system is mobile and can be controlled by an active computer control system.

[81] Fox, M. A., Yeh B. P., (2010), Intelligent Kinetic Systems, Massachustts Institute of Technology, Department of Architecture

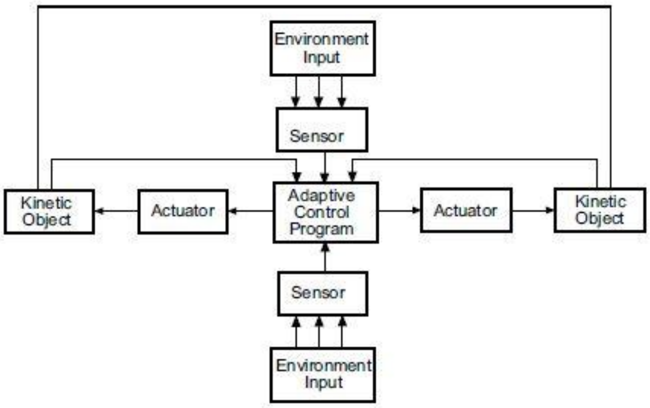

Figure 4.9.Diagram of Heuristic, Responsive in-Direct Control

< Source: Fox, M. A., Yeh B. P., (2010), Intelligent Kinetic Systems >

Moreover, according to heuristic, responsive in-direct control mechanism as shown in Figure 4.9., movement could be managed after a learning and experiental adaptation process according to heuristic optimizations of performative values. Guy Nordenson, who is a Professor in the Department of Structural Engineering and Architecture in Princeton University, evaluates these developments as a phenomenon of creating a building like a body, a system of bones and muscles and tendons and a brain that knows how to respond with his well-known expression:

"A dynamic environment without computation is like a body without a brain. "[82]

These developments could give a chance to buildings having more active role in our lives in the future as interacting with users dynamically according to their individual charactheristics and cognitive ability.

4.1.2.1.Mathematical Models of Intelligent Buildings

Sensors and actuators could be evaluated as hardwire side of an intelligent environment and computation of adaptive and responsive behaviors of architectural components through intelligent systems could be evaluated as the software side of an

[82] Guy Nordenson, As quated by Fox M., Kemp M., (2009) in Interactive Architecture

intelligent environment. The software side of an intelligent environment requires to use computation and mathematical models while constructing intelligent systems.

While constructing an intelligent environment as a living asset, pure physical approaches and physical models as applied to conventional buildings cannot model human behaviour-based systems for intelligent environments.[83] Mathematical modelling approaches which have uncertainty and flexibility characteristics, such as neural networks, expert systems, fuzzy logic and statistical models, offer much better ways of representing human behaviour. Recent advancements in artificial intelligence are making it possible to integrate buildings' learning and adaptation capabilities through solving uncertainty with mathematical models, which could solve a large set of equations and to formalize the reason about uncertain knowledge in buildings.[84] It is now possible that intelligent environment can not only offer better control over various building automation systems, but also have learning and adaptation abilities.

Conceptual models	**Probability-based models**
Simple analytical approach	AHP/ANP
	Bayesian inference
	Petri nets
Analytical models	**Knowledge-based models**
Linear dynamic approach	Neural networks
Non-linear dynamic approach	Expert systems
	Fuzzy logic
	Genetic algorithm

Table 4.2. Mathematical approaches applied to the intelligent buildings

<Source: Xiaoshu Lu , Derek Clements-Croome & Martti Viljanen (2009) Past, present and future mathematical models for buildings, Intelligent Buildings International, 1:1, 23-38>

As shown in Table 4.2., there are many different type of mathematical approaches applied to intelligent buildings, but since knowledge-based models are uncertainty models, they are more suitable for modelling increased complexity in intelligent

83 Lu X., Clements-Croome D., Viljanen M., (2009), Past, present and future mathematical models for buildings, Intelligent Buildings International, 1:1, 23-38, p.2

84 Ibid

systems and applied mostly for decision making and control mechanisms of intelligent systems.[85]

Firstly, knowledge-based models used for the structural design of buildings in order to create intelligent parametric templates within an automatic building system for rectangular plan type of buildings. In 1998, researchers developed an adaptive and predictive intelligent control system for earthquake loading of intelligent buildings. [86] Prediction of earthquake, structural identification and optimization were performed using neural networks, a genetic algorithm and fuzzy logic approaches.

In 2004, Liu developed an intelligent management system (a domain name system - DNS) using a knowledge-based system. Furthermore, in 2005, Rafael Alcalá proposed intelligent HVAC control system for intelligent buildings using fuzzy rules in combination with genetic algorithms.[87] And approximetly in the same time in 2000s, similar studies are realized for automatically detecting faults on HVAC systems. Finally, in 2006, Sierra proposed an intelligent system architecture based on neural networks, expert systems and agent technologies in order to improve the performance of intelligent buildings.[88] According to the proposal, the central computer contains a database for information and an expert system for decision-making, monitoring, visualizing and recording parameters with the help of the

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85 Lu X., Clements-Croome D., Viljanen M., (2009), op. cit. p.10

86 Tani, A., Kawamura, H. and Ryu, S., (1998), 'Intelligent fuzzy optimal control of building structures', Engineering Structures 20(3), 184–192.

87 Alcalá R., Benítez J.M., Casillas J., Cordón O., Pérez R.,(2003), Fuzzy Control of HVAC Systems Optimized by Genetic Algorithms, Applied Intelligence, v.18 n.2, p.155-177, March-April 2003

87 Sierra, E., García-Martínez, R., Hossian, A., Britos, P. and Balbuena, E., (2006), 'Providing intelligent user-adapted control strategies in building environments', Research in Computing Science Journal 19, 235–241.

regulations of local controllers. As comprehending from the example studies, combinations of more than one knowledge-based approaches are more effective and common for better performance of the whole ambient intelligence of an intelligent building.

Research on mathematical models lead to improvements in intelligent building systems. With the help of comprehending in depth the mathematical approaches and following new mathematical approaches, intelligent systems and consequently intelligent spaces could be able to improve more and more.

Artificial Neural Networks

The artificial neural network model is inspired by the biological neural network (Figure 4.10.), which consists of a huge number of connected neurons as processing units, each performing computation in parallel. According to neurology science, a human brain network system has a highly complex, non-linear dynamic system order[89], which could have the capability of memory, information processing and lastly a learning mechanism.

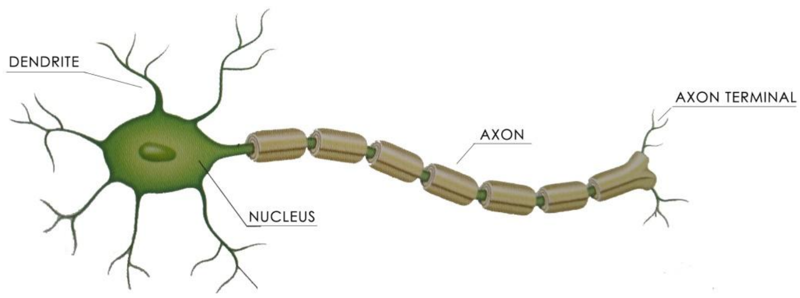

Figure 4.10. A Biological Neuron Model

<Source: Rita Carter, (2009), The Brain>

89 Miller P., (2016), Dynamical systems, attractors, and neural circuits, Volen National Center for Complex Systems, Brandeis University, Waltham, Massachusetts, 02454-9110, USA

Thanks to this analogical model (Figure 4.11.), artificial neural networks (ANNs) could have parallel processing capability, learning and storage ability using synaptic weights analogous to the strength of the synapse of a natural neuron.

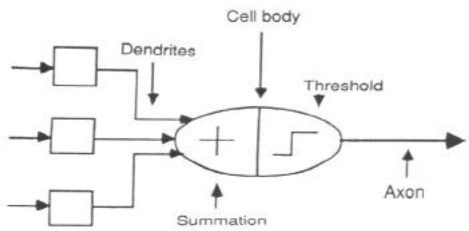

Figure 4.11. An Artificial Neuron Model (ANN)

<Source: Imperial College London, retrieved from http://www.imperial.ac.uk/computing, 12 June 2018>

Each neuron has a transformation mechanism, from input to output, which depends on its own self-conditions or environmental interactions. Interconnected neurons transfer the information via connections.

Mainly, each neural network consists of three main components:

1.Node Characther

2.Network Topology

3.Learning Rules[90]

Through training with given data while adjusting its weights and biases according to the input data, a neural network could manage to learn and perform particular tasks. Mathematically, this particular task often means minimizing a cost function which measures how close predicted output values are to target desired values.[91] The neural network approach have been widely used for identification, prediction, optimization and pattern recognition.

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[90] Zou, J. , Han Y., So S. ,edited by David J. Livingstone (2008), Artificial Neural Networks, Chapter 2;Overview of Artificial Neural Networks, p.17

[91] Lu, X.,Clements-Croome, D.,Viljanen, M., op. cit. p. 25

Expert systems

The term " Expert Systems" is often used to refer to any software of a computational system which makes intelligent decisions, however the proper use of the term concerns systems which use a spesific technology.[92] This spesific technology could be able to manage large quantities of information and use mainly knowledge based rules derived from human expertise while making decisions. Through an expert system, a computer acts as an expert consultant and makes inferences to arrive at a specific conclusion for a variety of problems that cannot be dealt with by other traditional approaches. [93]

```
IF      the date and time fall within the specified schedule
THEN    the system shall enter the occupied mode.
IF      the system is in the occupied mode,
THEN    the supply fan shall be turned on,
AND     the normally closed cooling valves and air dampers shall be controlled by a se-
        quenced PI (Proportional plus Integral) controller to maintain the room air tempera-
        ture set-point to 70 °F.
IF      the date and time fall outside of the specified schedule
AND     the room air temperature exceeds 55 °F
THEN    the system shall enter the unoccupied mode.
IF      the system is in the unoccupied mode
THEN    the supply fan shall be turned off, the heating valve shall be set to fully open and
        the cooling valve and outside air dampers shall be set to fully closed.
IF      the date and time fall outside of the specified schedule
AND     the room air temperature is less than or equal to 55 °F,
THEN    the system shall enter setback mode.
IF      the system is in the setback mode,
THEN    the system will remain in this mode until the room air temperature exceeds 60 °F.
```

Figure 4.12. The example rules of an expert control system

< Source: E. Sierra, A. Hossian, D. Rodríguez, M. García-Martínez, P. Britos, and R. García-Martínez, Optimizing Building's Environments Performance Using Intelligent Systems >

Firsly in 1970, a rule-based expert system appeared in AI to solve the problem of combinatorial complexity of learning requirements in neural networks. The background of the system, which contains information through IF-THEN algorithms,based on the rules (Figure 4.12.). However, with increasing number of

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[92] Clements-Croome D. (Ed.), (2004), Intelligent Buildings: Design, Management and Operation

[93] Lu, X.,Clements-Croome, D.,Viljanen, M., op. cit. p.32

rules, a rule-based exper system also suffer from combinatorial complexity of rules. [94]

Knowledge-based expert systems first appeared in the 1980s[95] and combine advantages of rules with learning adaptation, which is accomplished by fitting model parameters. Fitting model parameters could be managed with the help of selecting data subsets, whose number could be combinatorially large, corresponding to various models.[96]

Fuzzy logic

Fuzzy logic was introduced in the 1960s and simulates human reasoning process while decision-making. It is characterized by uncertainty and imprecision.[97] Fuzzy logic displays a different approach compared to traditional computation models due to the solutions having not exact outputs such as 1 or 0 like a Boolean logic. Through Fuzzy Logic, a conclusion, from an ambigious and imprecise data, could be inferred as decima numbers in probability rather than 0 or 1. In fuzzy logic, an element could belong partially to several subsets like defining a temperature as low, medium or high without exact values as shown in Figure 4.13.

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[94] Lu, X.,Clements-Croome, D.,Viljanen, M., op. cit. p.33

[95] Perlovsky, (2006), Recent development of physical theories has great potential in modelling human behaviours by classical physics mechanism

[96] Lu, X.,Clements-Croome, D.,Viljanen, M., op. cit. p.32

[97] Zadeh, L.A., (1965), 'Fuzzy sets', Information and Control **8**(3), 338–353.

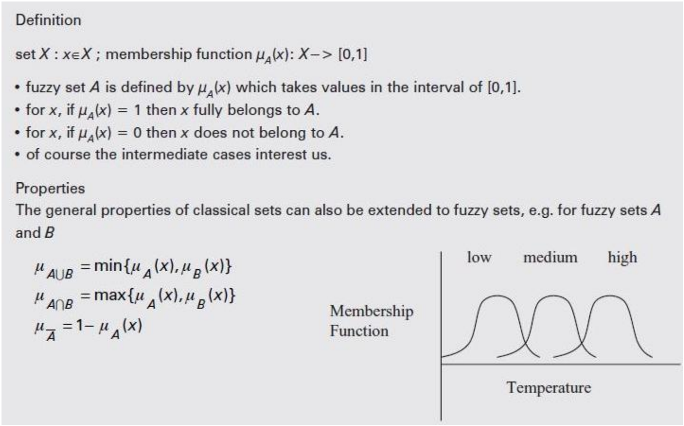

Figure 4.13. An illustration of definition and properties of a membership function

<Source: Xiaoshu Lu , Derek Clements-Croome & Martti Viljanen (2009) Past, present and future mathematical models for buildings, Intelligent Buildings International, 1:1, 23-38>

The problem can appear when the degree of fuzziness is too much or too little. If too much fuzziness is specified, the solution does not achieve good accuracy; if too little, it becomes formal logic.[98] Hence, it is hard to construct an intelligent system solely with fuzzy logic. Expert systems, neural networks and genetic algorithms are often preffered to combine for constructing more convenient intelligent systems.

Genetic algorithm

Evolutionary computation, which is inspired by natural selection, leads to the topic of genetic algorithms in the field of computation.[99] A genetic algorithm encodes a potential solution to solve optimization problems. The process of the algorithm starts with an initial population and then selects parents to produce the next generation using specific rules as shown in Figure 4.14. Over successive generations, the population evolves towards an optimal solution. A large number of iterations may be needed for a genetic algorithm to develop an optimal solution which is again a combinatorial complexity problem. [100]

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98 Lu, X.,Clements-Croome, D.,Viljanen, M., op. cit. p.33

99 Goldberg, (1989), Genetic algorithms in search, optimization, and machine learning

100 Lu, X.,Clements-Croome, D.,Viljanen, M., op. cit. p.33

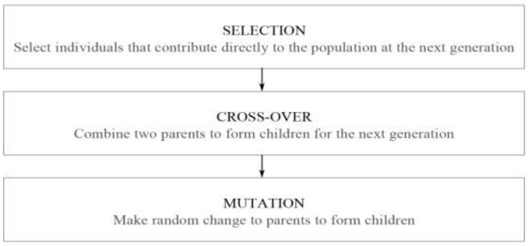

Figure 4.14. A brief summary of the genetic algorithm approach

<Adapted from Xiaoshu Lu , Derek Clements-Croome & Martti Viljanen (2009) Past, present and future mathematical models for buildings, Intelligent Buildings International, 1:1, 23-38>

Deep learning

Deep Learning (DL) is a newly-emerging Machine Learning theory, in which algorithms consist of multi-layer neural networks. Deep Learning computational models can learn multiple levels of abstraction through multiple processing of ANN layers.[101] In other words, thanks to deep learning algorithms, computers can learn from experience, understand the world in terms of a hierarchy of concepts and infer a function from observed experience. As the computer can gather knowledge from experience as input values, there could be no need for a human operation to formalize all of the knowledge needed by computer. [102]

However Deep Learning Algorithms demonstrate successful performance on some tasks compared to traditional machine learning models, deep learning models could also be less effective some tasks rather than traditional machine learning models. Advantages of deep learning algorithms are as follows:

[101] LeCun Y., Bengio Y., Hinton G., (2015), Deep Learning, Nature Vol 521

[102] Goodfellow I., Bengio Y., Courville A., (2016), Deep Learning, The MIT Press, Cambridge, MA, USA

- Deep learning algorithms have a strong capability on computing in-complete, ill-defined problems because their network topology is made up non-linear elements. [103]

-They have the capability of learning while changing its synaptic weights to adapt to the environment. [104] Traditional models lack the capability for active adaptation to the environment.[105] Perhaps the greatest advantage of them is their ability of 'learning' from observed data.[106]

- Deep learning algortihms could be conceived of as a ‘black box’ (Figure 4.15.) and this could be facilitate user's handling with algorithms because of no need for sophisticated mathematical knowledge.

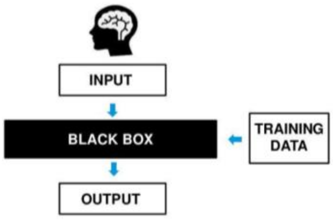

Figure 4.15. Computing in Black Box

<Source: https://www.slideshare.net/AlexPoon1/machine-learning-31769605, 30 June 2018>

-Compared to the other machine learning algorithms, they are very useful to handle complex data or complex tasks such as computation in real-time and recognition problems.[107]

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[103] Mas J.F., Flores J.J., (2008), The application of artificial neural networks to the analysis of remotely sensed data, International Journal of Remote Sensing, 29:3, 617-663

[104] Ibid

[105] He X., Xu S., (2007), Process Neural Networks : Theory and Applications, Zhejiang University Press, p. 20

[106] Miller, F.P.,Vandome , A.F., McBrewster , J. (Ed.), (2009), Competitive Intelligence, Business Intelligence

[107] Ibid

There is an example of Deep Learning and the other Machine Learning Algorithms speed and accuracy rates from an article from Hohai University. As shown in Figure 4.16., human activities are recognized using both traditional networks (Hidden Markov Model and Naive Bayes Classifier) and a Restricted Boltzmann Machine algorithm in a smart home. Compared with the traditional probabilistic models such as Hidden Markov Model (HMM) and Naive Bayes Classifier (NBC), the experiment results show that the deep learning model algorithm is better in terms of performance and accuracy ratio while recognizing human activities. [108]

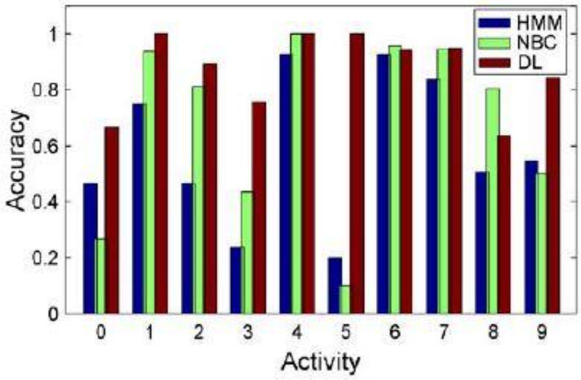

Figure 4.16. Comparison of the results of the Hidden Markov Model, Naive Bayes Classifier, and Deep Learning

<Source: Fang Hongqing, Hu Chen, (2014), Recognizing Human Activity in Smart Home Using Deep Learning Algorithm>

When an accurate mathematical or physical model is considered, there is no need to use deep learning algorithms. But when a complex, non-linear and ill-defined problems are considered, they have many advantages over traditional computational methods.

From the other perspective, they have disadvantages compared to traditional models as follows:

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[108] Hongqing F., Chen H., (2014), Recognizing Human Activity in Smart Home Using Deep Learning Algorithm

-Traditional machine learning algorithms works better on small data. Deep learning algorithms should be trained using large datasets to achieve high performance.[109]

-Traditional machine learning algorithms are processed easier than Deep Learning Algorithms due to the fact that they need less requirements of hardwire components such as fast and large RAM, SSD storage and GPU or a fast CPU.

As deep learning algorithms demonstrated superior performance (in accuracy and speed) in various tasks compared to traditional models, they are used mostly for the task of computer vision (object recognition), signal processing, pattern recognition, classification, optimization and different domain such as bioinformatics as shown in Figure 4.17.

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[109] Kalogirou S.A., (2009), Artificial Neural Networks and Genetic Algorithms in Energy Applications in Buildings, Advances in Building Energy Research, 3:1, 83-119, p.90

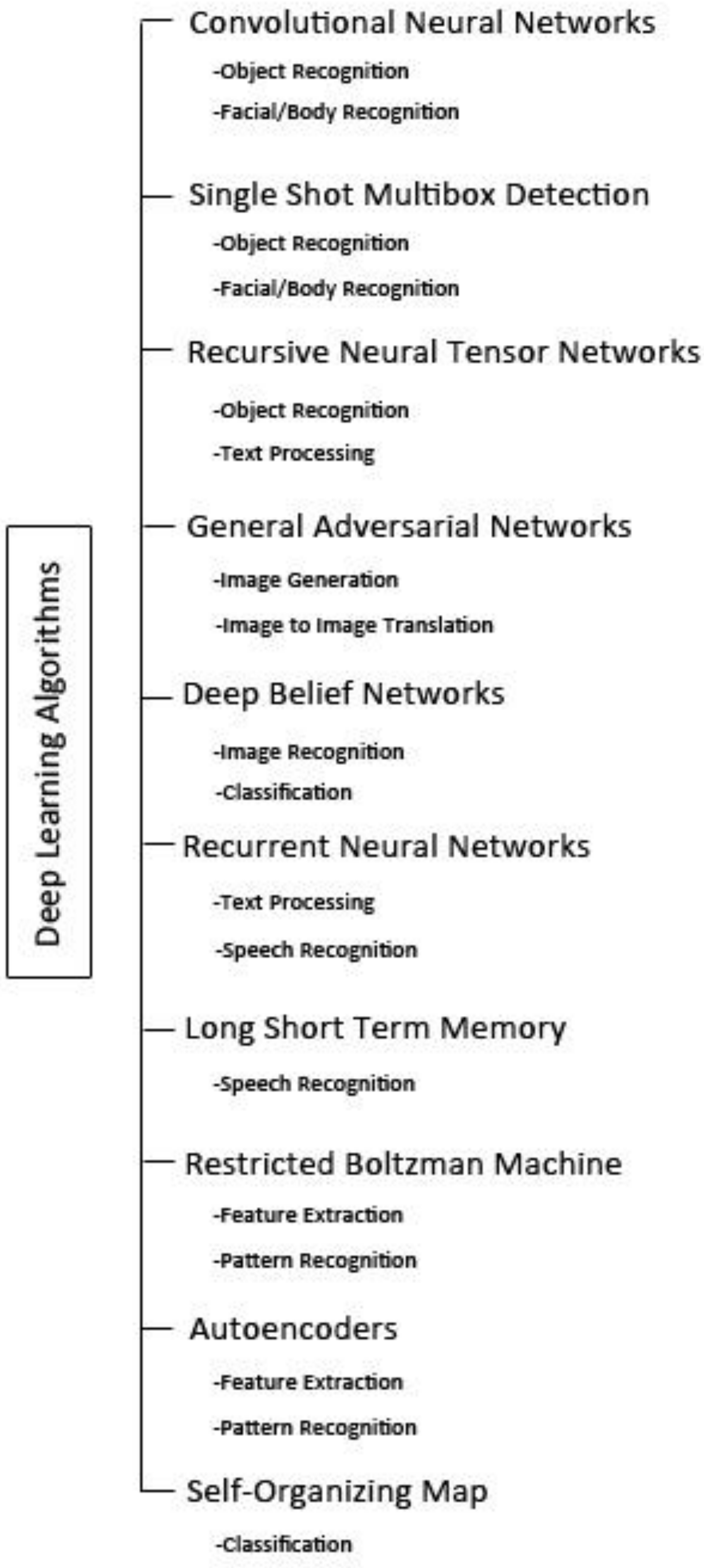

Figure 4.17. Commonly-Used Deep Learning Algorithms

In the context of architecture, the early use of ML algorithms in architectural space focused mainly on the fields of design generation, shape recognition, design space exploration and categorisation. Then, Vierlinger and Hofmann proposed a shift from directed search to creating a space with parametric design. According to the proposal, an application of genetic algorithms could provide multiple solutions for altering circumstances in the process of design generation. [110] Saunders and Gero use self-organising maps (SOMs) to estimate the novelty of a design and the performance of the design by categorising with representations of design situations, which are design solutions, problems and performance of the design. Harding uses the SOMs in the context of design space exploration. He argues the term of "dimensionality reduction" could be evaluated as a representation of architect's work which maps constraints and requirements in 3D space as hyper-dimensional inputs of the project.[111]

Recently, the last improvements on ML technology progresses on developing Deep Learning algorithms due to the ability of their speed of computation in real-time, solving capability of recognition problems. Furthermore, the strengthen of computational power, and also the proliferation of the algorithmic base through open libraries such as TensorFlow (https://github.com/tensorflow/), Keras (https://keras.io/), Caffe (http://caffe. berkeleyvision.org/), CNTK (https://github.com/Microsoft/CNTK), Accord.NET (accord-framework.net) and more, construct a base for the rapid maturation of Machine Learning practices in other fields and professions. Deep learning algorithms could have an enormous impressive potential for the improvement of interactive intelligent environments while bringing into them the power of perceiving and interacting with the users in real-time.

[110] Tamke M., Nicholas P., Zwierzycki M., op. cit. p.123

[111] Ibid., p.124

4.1.2.2. Agent-Based Architecture

The main issue of an intelligent environment is dealing with the relationships between user-building and environment-building. The charactheristics of an interactive-intelligent space like adaptiveness and responsive behaviors, which is the cognitive abilities gained by mathematical algorithms, could be shaped in form with the help of hardware side of the intelligent systems. The basis of this understanding is attained from robotics. In the field of robotics, responsive and adaptive behaviors could be formalized through embodied control systems, which means the hardwired systems conceptualized with computation.

In AI, control systems are referred to as agents. [112] The term " agent" means that an asset which gains memory and a logical system as properties with the help of AI. An intelligent agent could be able to manage respectively these three tasks:

1. It can represent input knowledge, receive and store them

2. It can solve problems with represented stored knowledge

3. It can give a solution (output), acquire new knowledge after the artificial system is running. [113]

Following the latest AI improvements, some researchers and architects developed projects and proposals using intelligent environments constructed by agents and multi-agent systems. In AI, Multi-agent systems have many distributed agents, which operates a set of behaviours in parallel, and each of which could decide when to become active or passive in real-time according to internal and environmental conditions (behavior-based approach). [114]

As shown in Figure 4.18. , one of the proposals of multi-agent systems in architectural space contains distributed processing units in each room. Room agents,

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[112] Callaghan V., (1999), Multi-agent architecture for intelligent building sensing and control

[113] He, X., Xu, S., (2007), Process Neural Networks, Zhejiiang University, China

[114] Ibid.

which are small embedded processors, control the sensors and effectors. And all of the agents are connected via a network. [115]

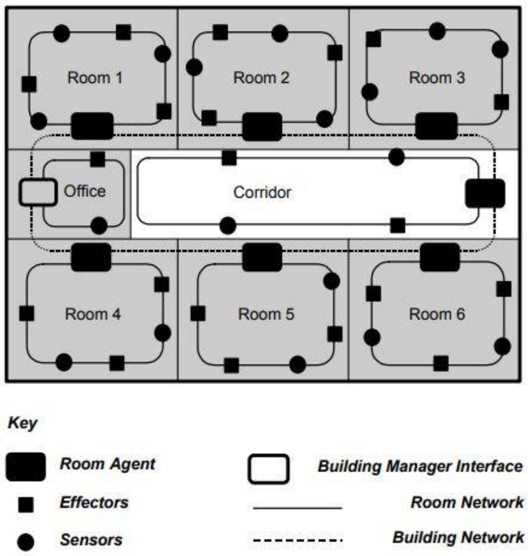

Figure 4.18. A Multi-Agent System Structure

<The ESSEX IB Macro Architecture, (1999), a proposal of multi-agent system for intelligent environment>

Depending on different situations, the network could allow the agents to share their information selectively and enable them to make its own decisions for responding to the particular needs of the person in a room rather than satisfying the needs of all the people in the building. [116] Multi-agent systems could provide the construction of an intelligent environment having complex intelligent systems.

In 2000s, Swarm Robotics is appeared in the field of ML as a subset of Multi-Agent Systems. [117] According to Swarm Robotics, each agent behaves as a part of collective behavior rather than behaving individually. [118] As mentioned above swarm robotics

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[115] Callaghan V., op cit. p.5

[116] Callaghan V., op cit. p.5

[117] Khaldi B., Cherif F., (2015), An Overview of Swarm Robotics: Swarm Intelligence Applied to Multi-robotics

[118] Yiannoudes S., op. cit. p.67

is inspired by swarm intelligence and constructed by many simple intelligent agents. As shown in Table 4.3., when compared with Multi-Agent Robotics, Swarm Robotics agents could be less intelligent and simpler, hence they could move homogeneously rather than moving individually and heterogeneously.[119]

	Swarm Robotics	Multi-Agent Robotics
Population Size	Variation in a great range	Small
Control	Decentralized and autonomous	Centralized and remote
Behavior	Homogeneous	Heterogeneous
Flexibility	High	Low
Scalability	High	Low
Dynamism	Dynamic	Dynamic

Table 4.3. Comparison of Swarm Robotics and Multi-Agent Robotics

<Adapted from An Overview of Swarm Robotics: Swarm Intelligence Applied to Multi-robotics>

Kas Oosterhuis, who is a famous architect, associated Swarm Intelligence with architecture and proposed "Hyperbody", which is defined as "a programmable building body that changes its shape and content in real-time". A hyperbody consists of many kinetic mesh structures, which behaves like actuators.These actuators interact with each other without having any knowledge about the overall structure just with the simple rules of adaptation: adjusting their speed, adjusting their distance and their directions.[120]

Recently, in the field of AI, the different behavioral approaches of multi-agent and swarm robotics have been tried to engage in multi-agent dynamic systems.[121] The main elements of a multi-agent dynamic systems are the agents and the information (i.e. sensing, control, and communication) links among these agents with a network.

[119] Khaldi B., Cherif F., op. cit. p.32

[120] Yiannoudes S., op. cit. p.112

[121] Gazi V., Fidan B.,(2007), Coordination and Control of Multi-agent Dynamic Systems: Models and Approaches

[122] Various types of multi-agent dynamic system models are developed, but one of them is the most appropriate for the proposal of this thesis, which is behavior-based multi-agent dynamic system. According to behavior-based approach, multi-agent system could manage to behave together dynamically without obstacles and reach the goals or targets without collisions while maintaining the geometric formation structure. With the help of algorithms, each robot computes on its own and comes to the its desired position according to position of the other robots. Each robot determines its formation position with respect to the leader and the neighbour robots, but the swarm center robot is not reponsible for maintain formation like the other ones (Figure 4.19). [123]

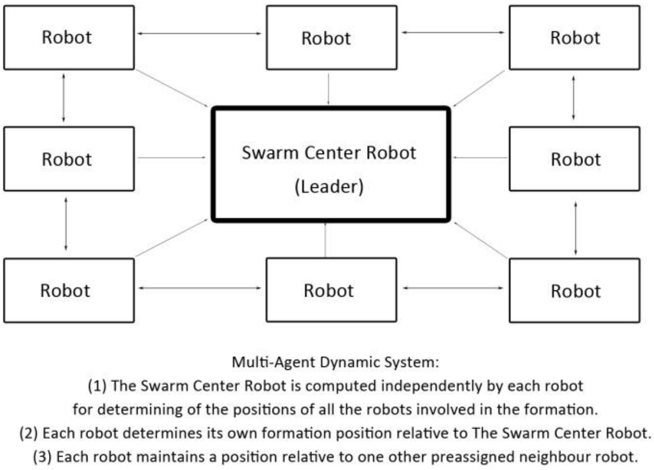

Figure 4.19. Multi-Agent Dynamic System

On one hand, the investments are progressing in the field of Multi-Agent Systems, on the other hand some new applications are born in the field of ML such as Multi-Agent Learning, which integrates machine-learning techniques in MAS and studies the design of Machine Learning Algorithms to create more adaptive agents.[124]

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[122] Gazi V., Fidan B., op. cit. p.90

[123] Gazi V., Fidan B., op. cit. p.91

[124] Tuyls K., Weiss G., (2012), Multiagent Learning: Basics, Challenges, and Prospects

With the following this type of developments, architects could devise more intelligent environments through robotics that assist users of a space and achieve the need of the people. Actually, an environment, which is equipped with assisted robotics, is not a new development. In 2008, the researchers from Orebro University carried out a project named "The PEIS [125] Ecology", which is an intelligent environment using robots, distributed sensors and effector devices. The system is not created as an ecology but consists of distributed sensors and robots, each of them could have the capability of perception and action. [126]

Figure 4.20. Living Room with Robot Astrid, PEIS Ecology, AASS Cognitive Robotics Systems Laboratory, Orebro University, Sweeden, 2018, Courtesy Alessandro Saffiotti

< <u>Source:</u> Socrates Yiannoudes, 2016, Architecture and Adaptation, From Cybernetics to Tangible Computing >

[125] PEIS: Physically Embedded Intelligent Systems

[126] Yiannoudes S., op. cit. p.78

Figure 4.21. Fridge and Living Room with transportation table, PEIS Ecology, AASS Cognitive Robotics Systems Laboratory, Orebro University, Sweeden, 2018, Courtesy Alessandro Saffiotti

< Source: Socrates Yiannoudes, 2016, Architecture and Adaptation, From Cybernetics to Tangible Computing >

As shown in Figure 4.20. and 4.21. robots can provide flexible usages and meet the needs of the users according to their internal operational rules.

However an environment, which is equipped with asissted robotics is not a new development. Constructing an interactive-intelligent environment by robots in the framework of multi-agent dynamic system could be a new approach for an architectural environment for strengthening human-building interaction. Furthermore, using deep learning algorithms for their user detection, user activity recognition and composing the dynamic behavior of a space could bring into the interactive and intelligent environments a new perspective.

CHAPTER 5

A CONCEPTUAL MODEL PROPOSAL FOR DYNAMIC ARCHITECTURAL ENVIRONMENT

This chapter is intended to draw a general framework of a comprehensive dynamic architecture approach, which could engage the powerful aspects of main dynamic architectural approaches such as intelligence, interactivity and transformability. Furthermore, ambient intelligence of such dynamic architectural environment will be discovered with construction and computation phases.

5.1. Improvement of Dynamic Architecture

As mentioned at the second part of the thesis, various types of Dynamic Architecture approaches multiply following the latest advancements in the field of computation, structural engineering and electronics. While each of them is more effective than the others on a chosen topic such as movability, behaving more intelligently or interactivity, all of them concern more or less meeting user/environmental needs and goals intelligently. After discovering the most powerful sides of each dynamic architectural approach, an advanced architectural environment could be developed which is composed of the effective aspects of each dynamic architectural approaches. This advanced architectural environment have probably all of these properties:

1.Interactive (two-way relationship between user-building and environment-building),

2. Intelligent for a whole building through intelligent control systems

3. Transformable for being more flexible in the way of achieving user/environmental goals.

Hence, a flexible, eco-friendly and interactive architectural environment could be constructed for a whole architectural building, even one day for a bigger scale environment. In this research therefore, a concept model of advanced dynamic architectural space and its construction methods will be proposed.

5.1.1. A Conceptual Model Proposal of Advanced Dynamic Environment

An advanced dynamic architecture could be managed with fully embracing the terms of interactivity, intelligence and dynamism. They are very related terms to each other due to the fact that while interactivity could be provided by intelligently dynamic behavior, dynamism could be realized by intelligent systems and intelligence of an environment could be shaped by dynamic architectural components. Mainly, the proposed model requires user and environmental awareness and dynamic components, which are enhancing the interactivity.

The three main charactheristics should be well-designed for this type of advanced architectural environments:

1.Interactive Communication: As there should be a communication in two-way circularity, interactive communication between user and space is realized with an interaction interface that works depending on sensation, computation and activation capabilities of a space. In an advanced architectural space, interaction interface composes the physical condition and the mental condition: cognition of an architectural environment.

2.Intelligent Behavior: Dynamic structures could be engaged with actuator technology for a consistent intelligent behavior of dynamic structures, which could be able to direct by the instructions coming from ambient intelligence. Intelligent behavior of the architectural components could be designed in a virtual environment through computer aided technology and simulation technology. Then, they are realized by dynamic structures, which has the ability of move in accordance with the composition designed by an architect.

3.Dynamic Structure Composition: Dynamic structure composition could be desinged in accordance with the desired behaviors of collective or individual architectural components, which could meet the user's needs and goals.

For a well-composed architectural environment in this way, an architect should devise the interaction interface with physical condition/s and mental condition of a space. While the physical conditions of a space, which are dynamic structure, materials and components, are shaped in the phase of construction, the mental conditions of a space such as interactivity and behaving intelligently could be shaped in the phase of computation. Inclusively, the cognition and physical conditions of an environment form the charactheristics of a space together. The charactheristics of a space is directed by mathematical algorithms as the software side of the building intelligent systems and they can structured by the sensory tools, agents and actuators as the hardwire side of these intelligent systems. On one hand, planning the software of an environment requires the knowledge about the algorithms for evaluation of the environmental inputs and making decisions on current and the next situations of architectural components. On the other hand, hardwire of an environment requires the knowledge about the structural engineering, sensor technology, robotics as intelligent agents and dynamic actuators for interactive dynamic action. The computation and engineering systems should work together in a coordination for a consistent intelligent environment.

5.1.2. Ambient Intelligence of The Conceptual Model

Interactive communication and intelligent behavior between user and architectural space could be provided by an ambient intelligence. As shown in Figure 5.1, in common intelligent spaces, step by step, sensors receive the input information, which are performative values or building-user interaction values, then they are transmitted to intelligent agents for evaluation through computation. After evaluation of the information in the system, actuators give reactions to the users or environment.

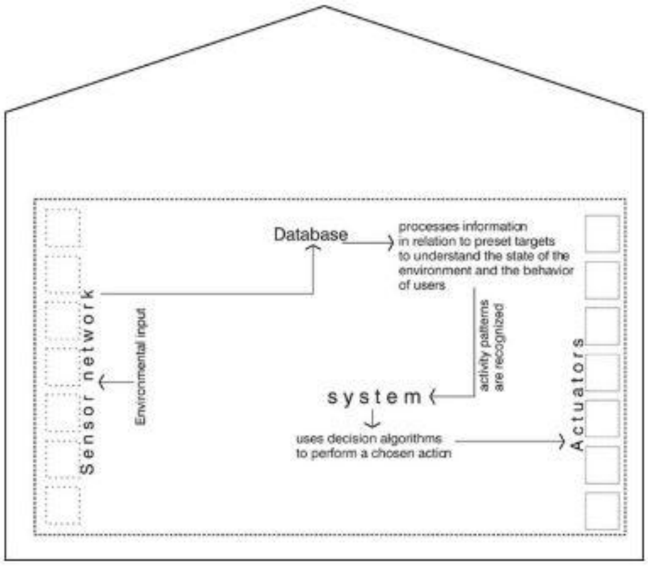

Figure 5.1. Diagram of Intelligent Environment

<<u>Source:</u> Yiannoudes S., (2016), Architecture and Adaptation, From Cybernetics to Tangible Computing>

Hence, as shown in Figure 5.2., an intelligent environment could gain sensation, computation and action ability, which construct the composition of building cognitive skills.

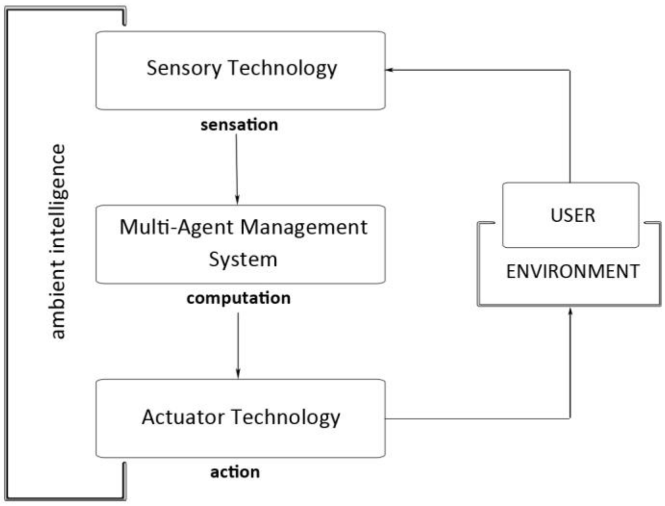

Figure 5.2. Information flow of classical ambient intelligence

<Adapted form Xiaoshu Lu , Derek Clements-Croome & Martti Viljanen (2009) Past, present and future mathematical models for buildings, Intelligent Buildings International>

Unlike common static intelligent building approaches, the conceptual model of the thesis inspired by the approach of multi-agent dynamic systems, which is consisted of physical agents as dynamic units. As mentioned before, a multi-agent dynamic system, in general, can be defined as a formation system connected via a network (for sensing, control, and communication) of a number of loosely coupled dynamic units called agents (i.e. a robot, a vehicle, or a dynamic sensor) The main objective of multi-agent dynamic systems is to collectively achieve goals that are difficult to manage by an individual agent or a monolithic system. [127] Various approaches have been developed for control mechanisms of multi-agent systems as shown in Figure 5.3., however behavior-based approach could be more consistent than the others as behaving reactively and having the properties of move-to-goal, avoid-static-obstacle, avoid-robot, and maintain formation.[128]

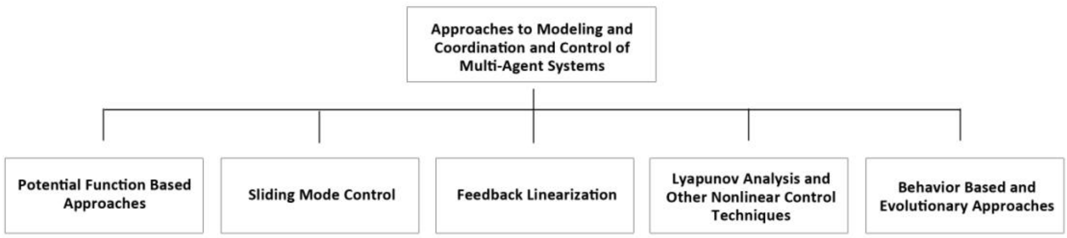

Figure 5.3. Approaches to Modeling and Coordination and Control of Swarms

<Source: Gazi V. and Fidan B., (2007), Coordination and Control of Multi-agent Dynamic Systems: Models and Approaches >

Behavior-Based Approach

Behavior-Based approach is one of the common multi-dynamic system approaches for coordinating groups of robots. According to the behavior-based approach, multi-robot teams could formation in harmony while avoiding collisions with obstacles and other robots, reaching goals/targets. The integration allows the system to reach goals and avoid collisions while simultaneously compatible with the geometric formation

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[127] Gazi V., Fidan B., op. cit. p.72

[128] Gazi V., Fidan B., op. cit. p.90

structure. Each robot computes its desired position in the formation based on the locations of the other robots. Using these behaviors the robots manage to a goal while avoiding obstacles and collisions with other robots and maintaining the formation. [129]

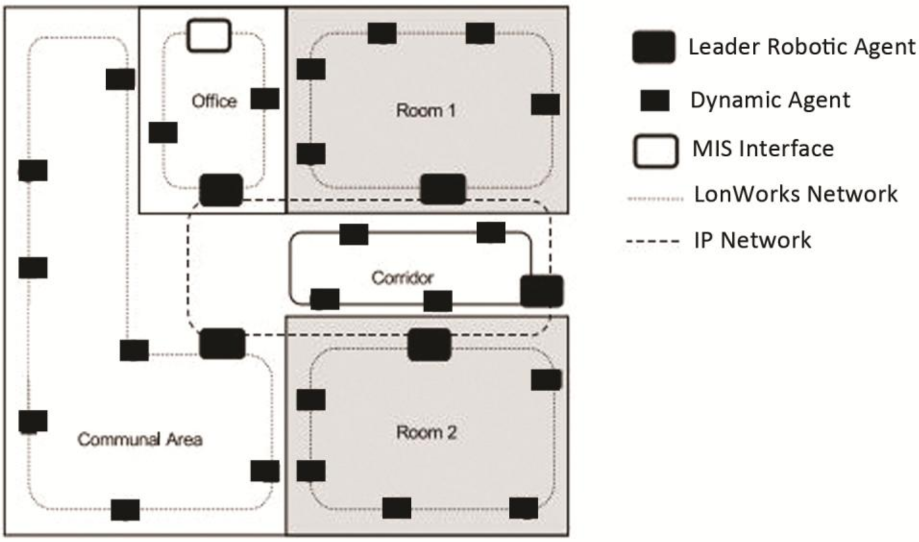

Figure 5.4. A behavior-based multi-agent dynamic structure building-wide architecture

<Adapted from H. Hagras et al., Hani Hagras, Victor Callaghan, Martin Colley, Graham Clarke, A hierarchical fuzzy–genetic multi-agent architecture for intelligent buildings online learning, adaptation and control >

An example of building-wide architecture of behavior-based multi-agent dynamic system could be given as shown in Figure 5.4. as room-based. Each room contains an embedded-agent, which is responsible from the other agents for the local control of that room. All embedded-agents (Leader Robotic Agents) are connected via a high level network (IPethernet in this case), thereby enabling collaboration or sharing of

[129] Gazi V., Fidan B., op. cit. p.91

information to take place where appropriate. In a building, all agents are connected together using a building services network (Lontalk in this case).[130]

Back to the proposed Ambient Intelligence, as multi-agent dynamic systems have a central leader robotic agent and the other agents, which behaves related to the central ones and the neighbours of its own. Inspired by multi-agent dynamic systems, as shown in Figure 5.5., the proposed model system consists of many robotic agents, each of them contains in its self its own intelligence in accordance with the composition.

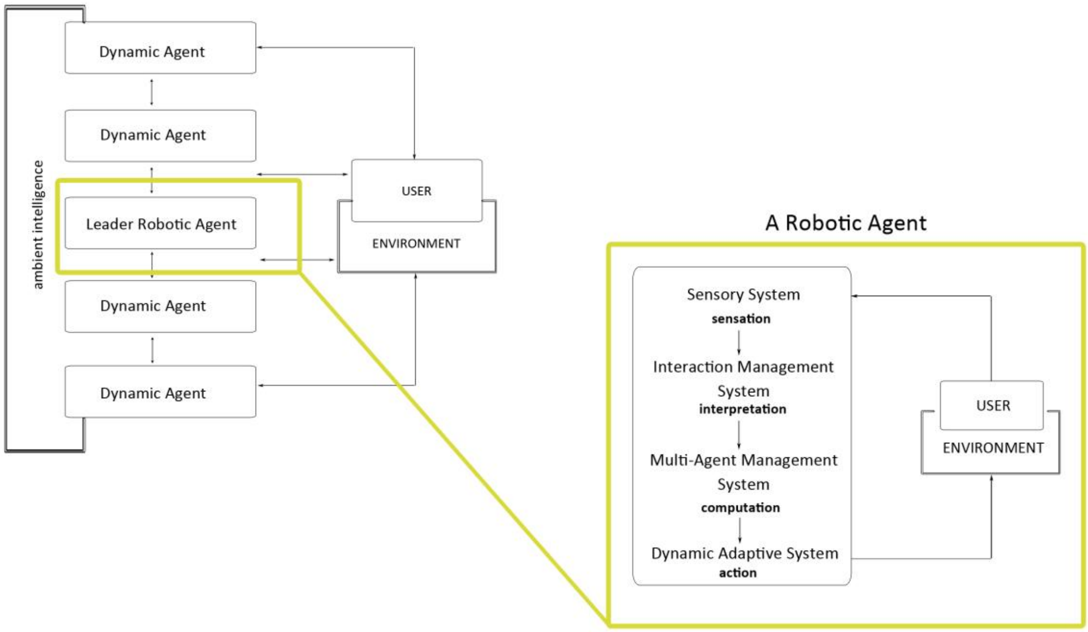

Figure 5.5. Information flow of proposed ambient intelligence

Each robotic agent contains various systems according to its role in the composition:

Sensory System: The Sensory system is a data receiving system, consists of sensory tools. It could enable the ambient intelligence to have sensation.

[130] Hagras H., Callaghan V., Colley M., Clarke G., (2003), A hierarchical fuzzy–genetic multi-agent architecture for intelligent buildings online learning, adaptation and control

Interaction Management System: The system produces an interpretation in the computational process, according to the circumstances of environment-ambient intelligence or user-ambient intelligence interactions.

Multi-Agent Management System: According to the interpretation process, the multi-agent management system could manage to select and direct the robotic agents for making a decision on an activation. While interaction management system is controlling the cognition of the system, multi-agent dynamic management system is controlling the dynamic behaviors of the system.

Dynamic Adaptive System: It consists of different type of actuators. Dynamic tools and dynamic robotic agents could be controlled automatically in accordance with the incoming command from the multi-agent management system to change adaptively for accommodating to changing human needs in a better way.

Clearly, step by step, sensors in agents, which could be responsible of any type of sensation, receive the input information, which are performative values or building-user interaction values.Then, the received information is processed in the robotic agent or conveying the central agent , depending on the situations, for interpretation process through computation with the help of Interaction Management System. After evaluation of the information, Multi-Agent Management System sends commands to the selected actuators and dynamic robotic agents for an action in accordance with the overall composition. Finally, dynamic agents and robotics give reactions interactively to the users or environment. Control mechanism actuation flow is shown in example Figure 5.6.

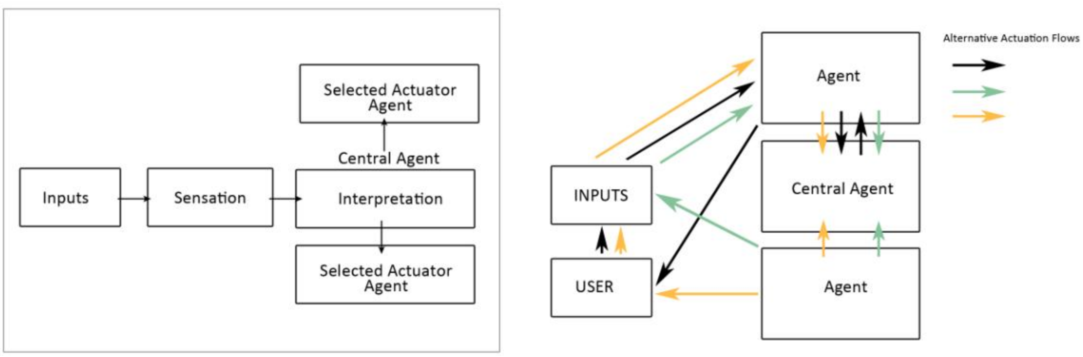

Figure 5.6.Actuation Flow of Control Mechanism

As a conclusion, dynamic relations between user and space could be managed by a multi-agent dynamic system consisting of intelligent dynamic agents. As required of interactivity, therefore, interactive communication between user and space could be achieved through this new proposed multi-agent dynamic system. The question will be how to structure this system in an architectural environment in the framework of aesthehic, philosophical, conceptual and pragmatic aspects. Hence, there could be created an interactive interface, which is constructed by building elements acting as intelligent agents.

5.2. Dynamic Internal Skin as a Human-Building Interaction Interface

In an architectural environment, the interaction between building and user could be managed successfully when it is mutual. The building also should be able to perceive and respond to the user just as the user does to the building. In order to achieve sensation and activation of a space in a collaborative order, a well-established interface design needs to be constructed. An ambient intelligence could be embodied through this interface within a building's internal and external skin.

As external skin of an environment has more strict borders and can create a need for intelligent communication with the other buildings, internal walls of an environment are seen as the interactive interface of the concept proposal. Internal walls of an architectural environment could be easily dynamic and interactive rather than external ones because there is no relationship between the outdoor environment.

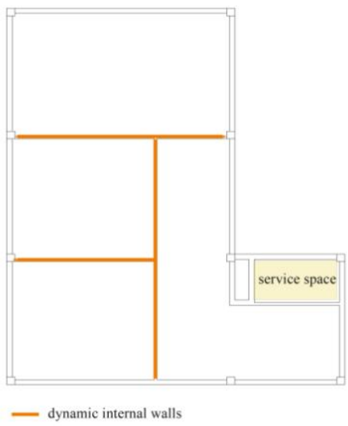

Figure 5.7. Dynamic Internal Wall

As shown in Figure 5.7., except the service based areas, all the inside walls have the potential of being dynamic interaction interfaces. For achieving the proposed interaction interface, the charactheristics both cognition and physical conditions as the structural needs of the dynamic wall system should be well-designed. The cognition of the interactive wall could be shaped and realized with the help of hardwire side of the wall, which is the whole structure of dynamic agents as an interactive interface. This type of interactive wall system could be able to provide a space to be multi-variable in function and to bring into a space maximum flexibility.

5.2.1. Designing the Structure of Interaction Interface

The structure of the interaction interface generates the physical conditions of the space, which are formed by dynamic internal walls. According to the proposal, the dynamic internal walls contain the ambient intelligence in its organization, which is the multi-agent dynamic system constructed as the interaction interface. Proposed wall system as an interaction interface could be managed by multi-robots, units equipped sensors and units behaving as an actuators. The collection of physical agent units are connected to each other and they could move in a 3 dimensional space to fulfill goal requirements.

Besides devising the overall composition of the wall structure, agent properties and dynamic interactions among the agents and dynamic behaviors of the agents should be designed as well.

5.2.1.1. Materials and Methods

As mentioned in the third chapter, a dynamic architectural element or component could be easily produced by prototype elements gained dynamism through an actuation mechanism. Advances in fabrication technologies enable the production of agent modules/lightweight structures with desired physical properties in pieces and panels, and also enable to combine them and apply with the help of digital fabrication tools such as Computer Numerical Control Machine (CNC), 3D printer, industrial robotic and drone as shown in Figure 5.8.

Figure 5.8. 3d Printer and CNC Machine

<Source: Voxel Factory, retrieved from https://www.voxelfactory.com/, 26 August 2018>

After production, the technology could be transferred through integration with electronic circuits or another type of forcing power elements, which bring into the object ability of movement, hence the architectural elements could easily be converted from being static to being dynamic. Therefore, agents of a multi-agent system also could be able to produce as modules or lightweight structures with the help of fabrication technology and can gain sensation, activation or both of them as properties with transferred technology.

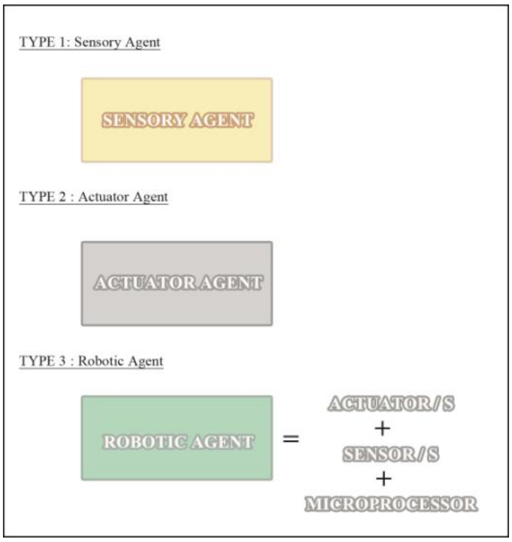

Figure 5.9.Agent Types of Proposed Wall System

As mentioned before, a multi-agent dynamic system has a central robotic agent and the other agents, which are led by this central agent. While leader robotic agent is planned to stable and more clever than the others as containing all of the control system mechanisms such as sensory tecnology, interaction management system, multi-agent management system and actuator technology, the other dynamic agents could be designed solely as a smart sensory agent, actuator agent or robotic intelligent agent as shown in Figure 5.9.

Production of Sensory Agent: After producing as modules/lightweight structures, they could gain sensation with the help of visual chips or resistors (i.e. light-dependent resistor, pressure-sensitive resistor, force-sensitive resistor and heat-sensitive resistor) and added electronical equipments. Hence, environmental inputs could be acquired from the environment.

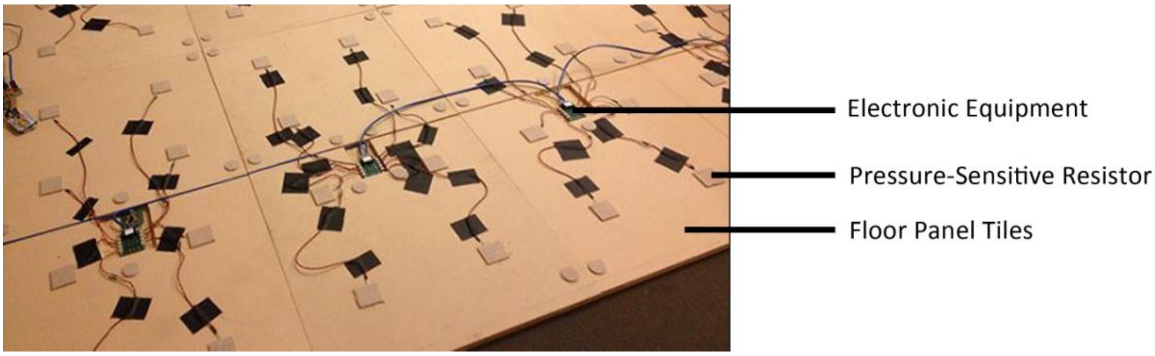

Figure 5.10. Production of Sensitive Floor Tiles

<Source: Pressure-Sensitive Floor Tiles, retrieved from https://sean.voisen.org/, 20 August 2018>

In Figure 5.10., an example of pressure-sensitive floor tile as a sensory tool is produced by integrated resistors and electronical equips. Sensory agents, which will be used within the proposed interaction interface, could be varied according to their ability of sensation such as distance, color, proximity and motion or it can composed all of them like a parallax sensor.

Production of Actuator Agent: After producing as modules/lightweight structures, they could gain activation with the help of an activation force (Figure 5.11) As the proposed wall system contains intelligent agents modules/lightweight stuctural elements, the activation force will be probably based on electrical power, which could be transformed easily into mechanical power. Hence, processed outputs could be transferred to the environment through actuator agents.

Figure 5.11.Activation Power Force of Dynamic Wall

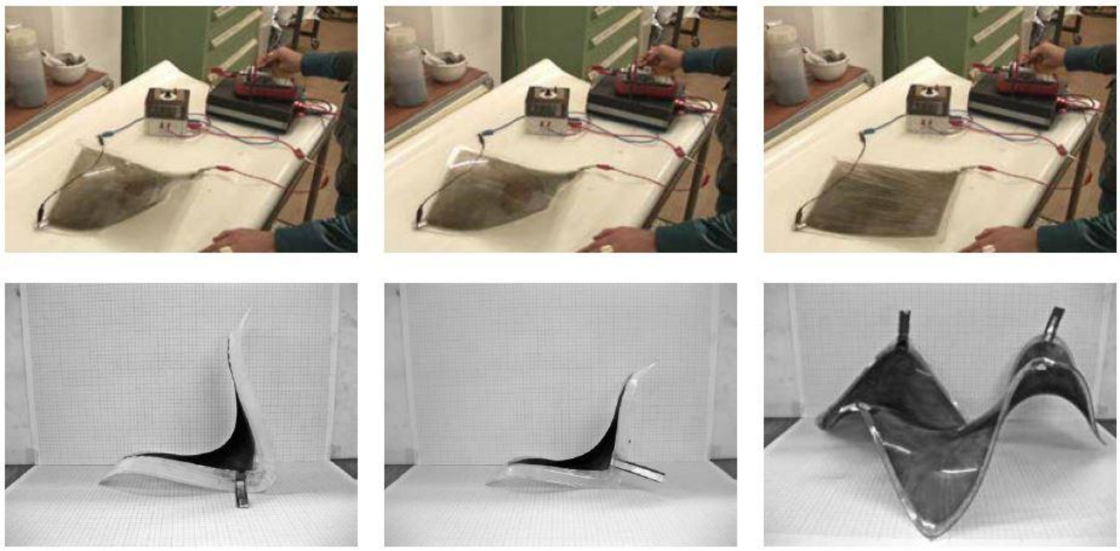

Figure 5.12. Shapeshift, Manuel Kretzer

An example of this process shown in Figure 5.12., the ShapeShift Project by Manuel Kretzer is an experimental project that explores the future possibilities of electroactive polymers(EAP) in architecture. He used dielectric elastomer surfaces, which are smart materials transforming electrical energy into mechanical force. After integration of electronical circuits, when powering the electrical energy, the desired three-dimensional motion was achieved.[131]

Production of Robotic Agent: They contains both sensor/s, actuator/s and also a microcontroller, which is a microcomputer including processor, memory and input, output functions in its internal configuration.

As shown in Figure 5.13., sensors gather analog information, after the analog information is converted to digital signals by Analog-to-Digital Converters, they are

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[131] Fox M.(Ed.), op. cit. p.140

transmitted to microcomputers. Microcomputer processes the information using coding and then with the help of ethernet or wifi, inputs could be transmitted to the central agent if it is necessary for the composition of whole system. According to coming command for desired movement, microcomputer of the robotic agent or the central agent makes a decision on activation of actuators. Lastly, the movement is realized via actuators after transforming the computational data inputs from digital to analog with the help of digital to analog converter(s).

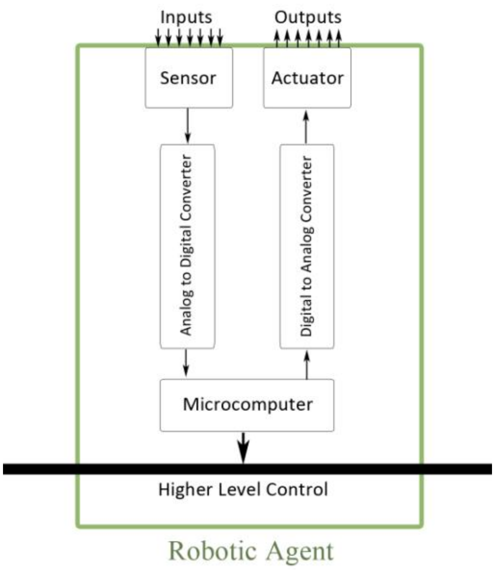

Figure 5.13. The Block Diagram of an Electronic Control System for a Robotic Agent

For constructing a consistent formation of the multi-agent dynamic system, after devising each agents, formation analysis of the structure composition should be calculated with the help of engineers about agent modules and their relationships as below :

1. Formation Control Graphs and Underlying Graphs

2. Rigidity and Persistence

3. Neighborhood [132]

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[132] Gazi V., Fidan B., op. cit. p.72

And finally, according to scale of an architectural environment, dynamic agents could be applied to the buildings manually or with the help of drone like shown in Figure 5.14.A drone could carry the architectural elements by flying and to place sensitively them according to the digital values. Hence, it can save the money and time during the construction.

Figure 5.14. Flight Assembled Architecture

<Source: Yiannoudes S., 2016, Architecture and Adaptation, From Cybernetics to Tangible Computing>

5.2.1.2. Dynamic Behaviors of the Structure

Designing dynamic behaviors in an architectural space requires an interdisciplinary study, which is based on mathematics, mechanics and structural engineering. However, in the process, architects should define the rules of anticipated dynamic movements through tracing the positions, actions, paths and patterns of a movement. Both individual movement of an architectural component or choreographed movement of more than one architectural elements requires a predetermined plan of the dynamic movement in sequences of space and time. Defining the dynamic movement process, capacity and type according to the desired goal of the design concept, the contributions of the interactive interface to the architectural environment are determined by the architects.

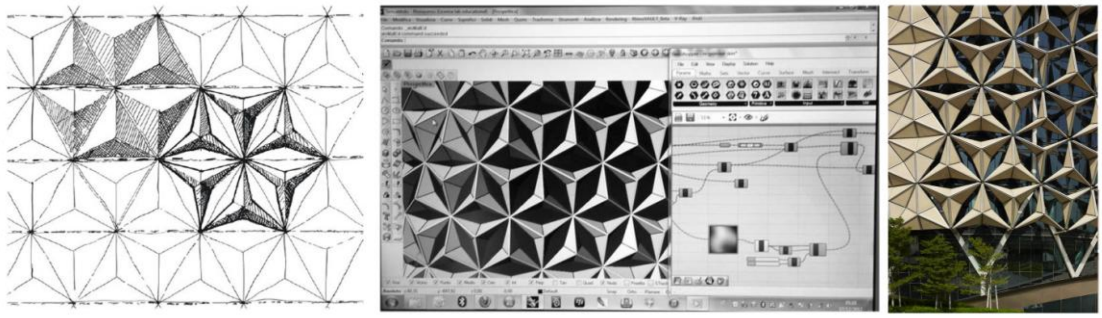

Figure 5.15. Designing dynamic façade of Al Bahr Towers through Grasshopper (Graphical algorithm editor for Rhino)

<Source: Al Bahr Towers, retrieved from http://www.ahr-global.com/Al-Bahr-Towers, 12 July 2018>

As shown in an example from the design process of Al Bahr Towers in Figure 5.15., with the help of many digital tools such as 3dMax, Rhino, Maya, architects could design dynamic architectural elements and their possible movements in sequences of space and time while considering the different situations of their possible size, shape and surface. Even, spesific components could be investigated and the kinetic behavior of the entire system could be realized within the digital environment.

In a digital environment the proposed wall movements could be defined before construction. For the proposed wall system, dynamic behaviors of interactive walls can actualized in two ways:

1. Macro-Level Dynamism

2. Micro-Level Dynamism

1.Macro-Level Dynamism of Interactive Interface

As mentioned before in the third chapter, macro-level dynamism refers to spatial dynamism based on spatial movements, which could be ended with changing of spatial configurations and it is mostly based on the movement of basic mechanisms around the axis as shown in Figure 5.16. Generally basic movement types, such as rotation, translation and combination of them, could be realized around an axis with the help of hinges and joints.

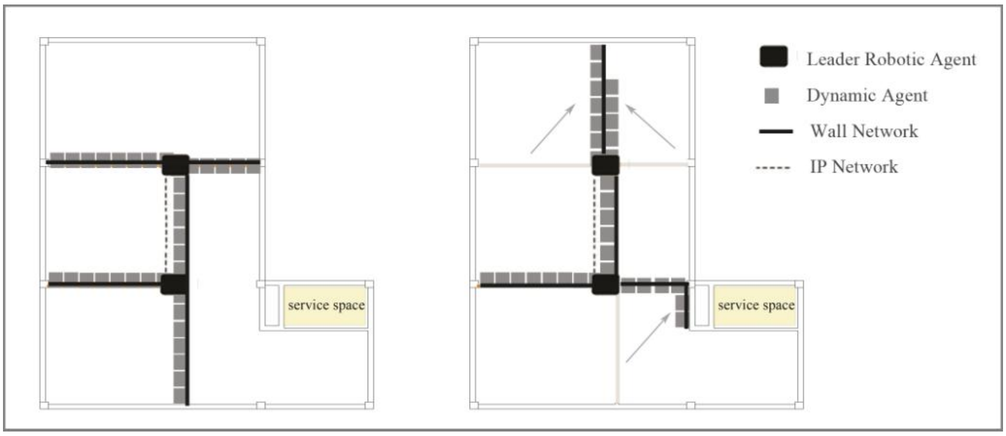

Figure 5.16. Dynamic Internal Walls

As being a multi-agent dynamic system, the wall structure is designed as a leader-follower structure. Hence, each dynamic agent tries to arrange its position in accordance with the leader robotic agent and its neighbour agents with the help coming commands from the multi-agent management system.

Potential conflicts can occur resulting from the need of two spaces. Tristan D'Estree Sterk, who is a faculty member in the Department of Architecture in the School of the Art Institute of Chicago, discusess that the coordination of responses at coincident. According to his opinion, a shared movable partition wall as an actuator could need to respond two spaces at the same time in different ways.[133] Hence, while decision-making process the system should evalute two different space qualities together for a consistent behavior decision or could make an optimization for spaces.

2.Micro-Level Dynamism of Interactive Interface

Micro-level dynamism, in other words, dynamism of architectural elements is based on movement, transformation or formal deformation of architectural elements as mentioned in the third chapter. As behavior-based multi-agent dynamic systems are control systems, which could give a chance to move whole agent structure

[133] Kolarevic B., Parlac V. (Eds.) , op. cit. p.14

collectively as swarm robotics and also to move each agent as individual, the proposed dynamic wall system could interact with the users through its individual agents.

As each agent could be smart or dumb compared to the other, their dynamic interaction behavior could be changable from one to another. Whereas multi-agent team(swarm robotics) should be always cooperative, fully competitive agents should be always self-interested. In the grey area in between them, in multi-agent dynamic systems, the cooperation is optional.[134] Hence, if there is a need for self-interested behavior each robotic agent could make its own decisions in a harmony with the composition of the whole structure.

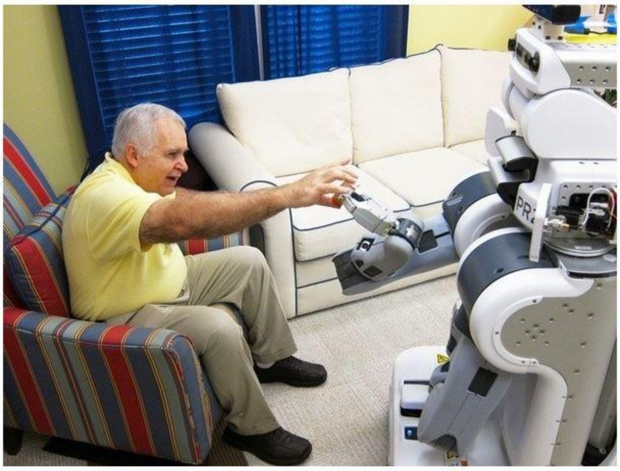

Figure 5.17. Assisted Robotic

<Source: WEBTEKNO retrieved from http://www.webtekno.com/, 20 August 2018 >

Recently, assisted robotics have been used for assisting elderly and people with disabilities for the purpose of helping and assisting them to achieve their needs and goals. Inspired by them, each intelligent robotic agent could be defined as built-in robotics in the proposed interactive wall and they can behave like an assisted robotic for the purpose of achieving the goal and requirements of the user and space.

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[134] Busoniu L., De Schutter B., Babuska R., (2005), Learning and coordination in dynamic multiagent systems, Delft University

5.2.2. Designing the Cognition of Interaction Interface

The main force effect of the dynamics in architecture is based on dynamic interactions between human-building and environment-building. Proposed model has been thought of as an user-building interaction dependent system, which establishes a two way communication between user and space.

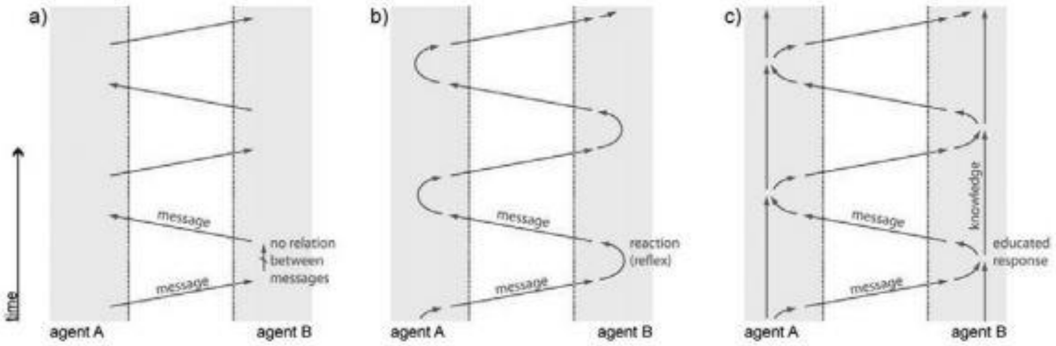

Figure 5.18. a) Responsive b) Reactive c) Interactive Communication

<Source: Jaskiewicz T. , (2010), (In:)forming Interactive Architectural Systems, Case of the xMAiA Meta-model>

As shown in Figure 5.18., the communication between two agents (two agents are user and building in this case) can be in various types. But through an interactive interface, a building could interact with its users mutually and charactheristically in different conditions while learning from them.

As mentioned above in Chapter 4, Eastman's model proposes a distributed system of devices that operate autonomously and they are individually controlled by users through local feedback loops. He lead to the horizon of interactive communication in two-way circularity between user and space for the future works. Approximately at the same time, Yona Friedman proposed a model also for controlling architectural adaptation. Friedman's model puts building users in direct control of architectural adaptations, as a centralized control system. Then, Tristan d'Estree Sterk tried to combine these two models and proposed another model "hybridized model of control", where both local and global (top-down and bottom-up) control is possible.[135]

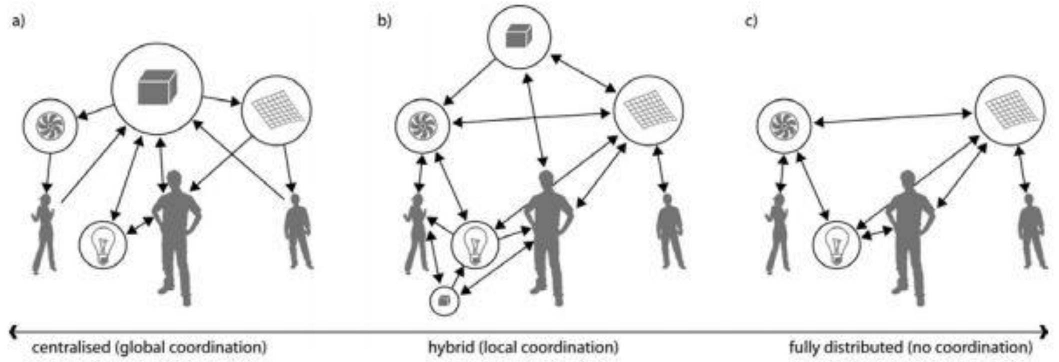

Figure 5.19. Information flow in centralized (a), hybrid (b), and distributed (c) concepts of user interactions with architecture

<Source: Jaskiewicz T. , (2010), (In:)forming Interactive Architectural Systems, Case of the xMAiA Meta-model>

The common control models are shown in the Figure 5.19., box icon represents the system controller and other icons represent active sensing and effecting building components.[136] The proposed model could be evaluated as a hybrid control model because of its local control ability. The model can work as a local system or a global system according to the commands coming from the multi-agent dynamic system. And in the future, the model could be improved more and more depending on improvements in control system mechanisms.

While the control system, which is multi-agent management system, conducts the physical conditions of the system as controlling the structural behaviors of the interaction interface, the interaction management system, which interprets the coming inputs and evaluates them, define the cognition of the model. As mentioned before, there are studies on the contol system mechanisms mostly due to coming the profession of engineering but there is not much studies on the cognitive abilities of

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135 Jaskiewicz T. , (2010), (In:)forming Interactive Architectural Systems, Case of the xMAiA Meta-model

136 Ibid

an architectural environment, which forms the cognition of a space. Hence, one of the main question of this study is on how to improve the cognition of the proposed model as an interaction interface.

5.2.2.1. Composition of Interaction Management System

An interaction management system evaluates the inputs for interpretation process in accordance with meeting user needs. In intelligent building research,"meeting user needs" corresponds generally meeting the user's thermal comfort, privacy, security, functional flexibility and well-being as shown in Figure 5.20.

Figure 5.20. General Intelligent Building Priorities

But, buildings do not merely provide physical shelter and protection as providing people thermal comfort and safety and so on; they can also effect user heatlh condition and consciousness mentally.[137] Through changing the body conditions of a human such as heart rate, blood pressure or breathing, human health and mind can be affected on the processes of memory, emotions, concentration, distraction and even decision making as shown in Figure 5.21.[138] The surrounding environment can

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[137] Ong B.L., Pallasmaa J.(Eds.), (2013), Beyond Environmental Comfort, p.91

[138] Dougherty B.O., A. Arbib M.A., (2013), The evolution of neuroscience for architecture: introducing the special issue, Intelligent Buildings International

directly alter a human's health and mind conditions, can even change the structure of the brain.[139]

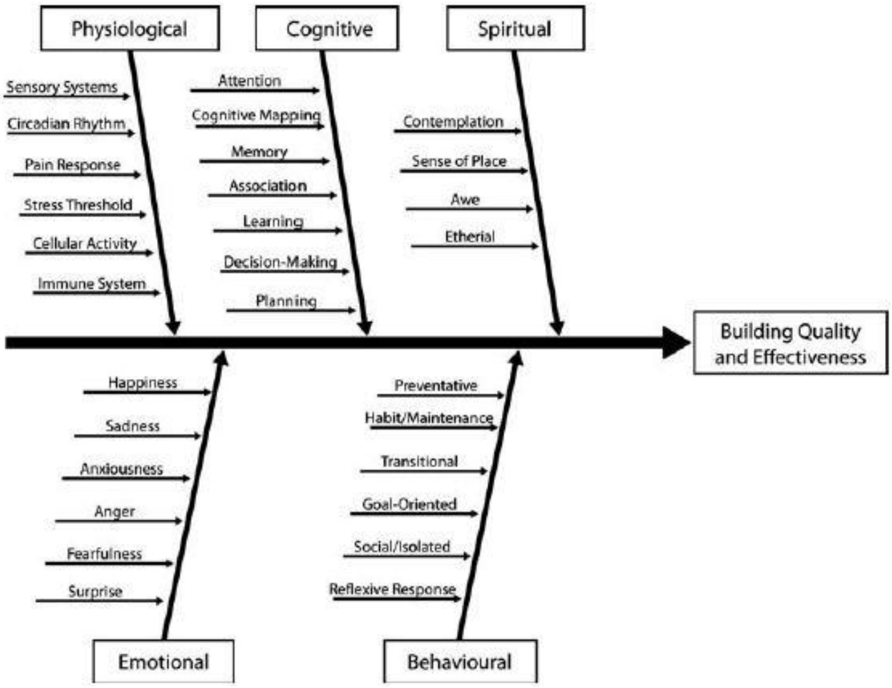

Figure 5.21. Affection of the User

<Source: Maria Lorena Lehman (2011) How sensory design brings value to buildings and their occupants, Intelligent Buildings International, 3:1, 46-54>

A well-designed sophisticated ambient intelligence can change users' behaviors, emotions, and health conditions in a good way through mutual interactions. As mentioned before, interaction requires mutual communication between user and space. The control system of an interactive architectural space fed with feedback loops(Figure 5.22.) Through feedback loops, the system could manage to learn directing intelligent behavior in complexity.

[139] Lehman M.L., (2011), How sensory design brings value to buildings and their occupants, Intelligent Buildings International, 3:1, 46-54

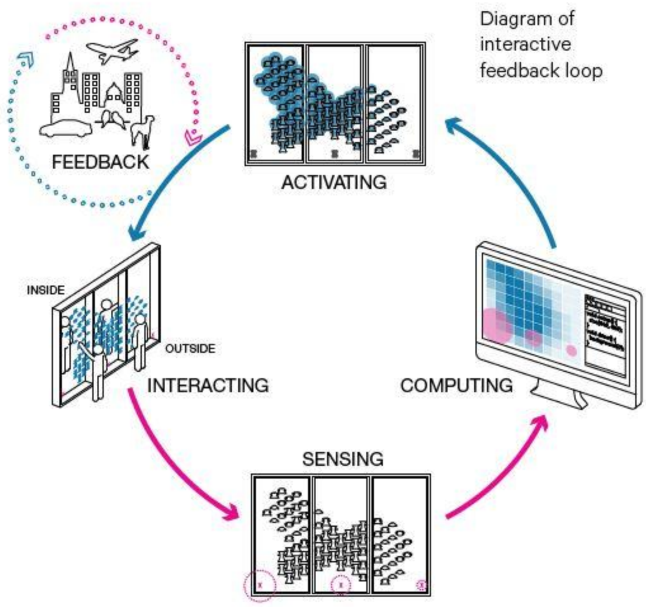

Figure 5.22. Feedback loop in interactive architecture

< Fox M.(Ed.), (2009), Interactive Architecture: Adaptive World >

Learning of an ambient intelligence requires both negative and positive feedbacks. Through the evaluation of each interaction feedbacks, an environment can modify and improve itself over time.[140] On one hand feedback loops strengthen intelligent dynamic behaviors, on the other hand feedbacks could also have the capacity of strengthing the cognition of a space while improving the interpretation ability of the interactive management system. Hence, with its own cognitive skills, a space could have the quality of changing its users life in most effective way.

[140] Lehman M. L. , (2017), Adaptive Sensory Environments: An Introduction, p. 71

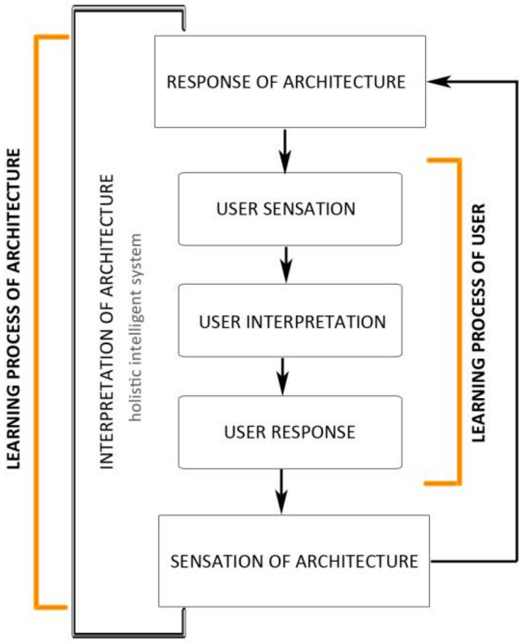

Figure 5.23. Mutual Learning

<Source: Adapted from Maria Lorena Lehman, (2017), Adaptive Sensory Environments: An Introduction >

The cognition of a space could be shaped through learning from each feedback loops as shown in Figure 5.23. While following the user goals and expectations from an environment such as temperature quality, a space could learn and adapt itself by arranging the temperature in different times in accordance with his needs. Hence, an environment is learning from the users, while a user is learning from the environment mutually. Mutual learning with each feedback loop will result in personalized experience, which can be defined as providing the needs of a user according to the user personality and characteristics.

Especially, museums and exhibition galleries could facilitate the user learning ability while directing them and learning from them. As an example of it, in her book, Maria Lorena Lehman proposes an adaptive museum, which can provide a personalized experience for each visitor. After each interaction with the visitor, the museum and its exhibits get smarter because museum can learn from each interaction and improve the way for tuning future visitors. She mentions that while a 35-year-old visitor is learning mainly visually, a 65-year-old visitor is learning with hands-on approach.

The goal of the proposed museum is to teach within the context of how they like to learn, how their existing skills relate to the subject at hand, and to what they are most curious about discovering. Therefore, a museum could be an enjoyable, educational, personal, and inspiring experience.[141]

Figure 5.24. "Playing" and "Learning" with Programmable Bricks

<Source: Mindstorm LEGO retrieved from https://www.lego.com/en-us/mindstorms/build-a-robot, 30 August 2018 >

Personalized experience also could be used for educational environments. Due to the fact that the children learn mostly by playing, similar to Mindstorm Lego logic (Figure 5.24.), using the kinaesthetic learning, an interactive interface could promote to learn through playing with children. Even, in heathcare environments, it could also promote the children patients to be healthy by playing with them in the concept of play therapy.

To conclude, an interactive interface has an interaction management system for interpretation of environmental inputs and the interface could improve its cognitive skills with each feedback loops while interacting with user and environment. Hence, a space gains a cognitive capacity to provide users personalized experiences for meeting their needs and goals.

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[141] Lehman M. L. , op. cit. p. 170

5.2.2.2.Computation of Interaction Interface

As shown in Figure 5.25., an interaction interface as a multi-agent dynamic system gains its cognitive ability through computation while evaluating the inputs and giving an intelligent reaction as outputs.

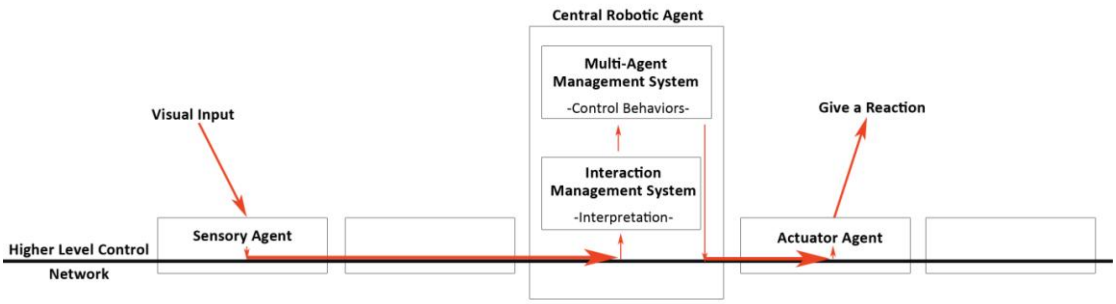

Figure 5.25. Workflow of Multi-Agent Dynamic System

Computation occurs in an interaction interface in two steps:

1. In Interaction Management System: In interaction management system, the inputs are evaluated with mathematical algorithms and acquired an interpretation according to inputs. Then, the interpretation output is sent to the multi-agent management system for controlling the intelligent behaviors.

2. In Multi-Agent Management System: According to coming interpretations from interaction management system, the system controls the whole structural behaviors in a harmony while making decision on activation of dynamic components.

The various algorithms could be used for Interaction Management System and Multi-Agent Management System as mentioned mathematical algorithms in the forth chapter. As the various algorithms of multi-agent management systems have been develeoped for years by engineers, the controller algorithms of multi-agent management system in detail is not a topic of this thesis. One example of it is reinforcement learning in multi-agent dynamic systems for making decisions on intelligent behaviors (Figure 5.26.)[142]

[142] L. Bus¸oniu, B. De Schutter, and R. Babuska, (2005),Learning and coordination in dynamic multiagent systems, Delft University

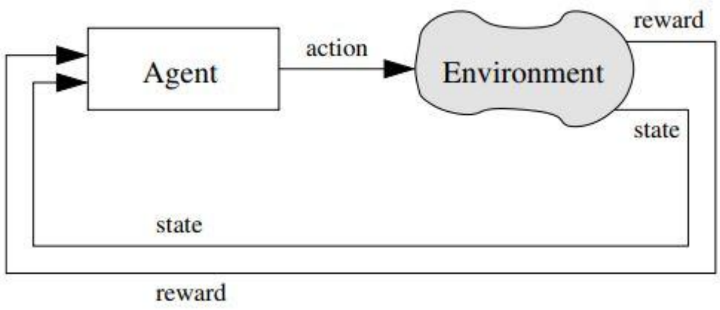

Figure 5.26. Reinforcement Learning Model

< Source: L. Bus¸oniu, B. De Schutter, and R. Babuska, (2005),Learning and coordination in dynamic multiagent systems, Delft University >

Interaction management system could be evaluated as a system defining cognitive skills of the model, which construct the personality of an architectural environment. Hence, the system could be improved by using deep learning algorithms for enhancing cognitive skills of interaction interface such as user identification and user behaviour recognition as Deep Learning algorithms have successful performance on some tasks such as computation in real-time, identification and recognition (i.e. object, pattern). Hence, they could provide the proposed wall system with an advanced awareness capacity, which is needed by an interaction interface.

User Identification

For responding to the needs of users, a space should be aware of its users fully. As mentioned above an ambient intelligence could recognize the users in real-time using sensory tools.

Figure 5.27. Pupil Detection

<Source: BAYOMETRIC, retrieved from http://www.bayometric.com/, 20 August 2018 >

Using deep-learning algorithms, the proposed interaction interface can follow the users' physiological and physical health conditions while detecting of their pupils (Figure 5.27), heart rhythms, body temperature and their actions time by time with the help of sensory tools, and with the help of interaction interface the space can improve its thermal comfort, health conditions and functional requirements while arranging the architectural qualities such as noise, temperature, air quality and lightning to the most appropriate level or directing the users for achieving a goal through actuators(Figure 5.28).

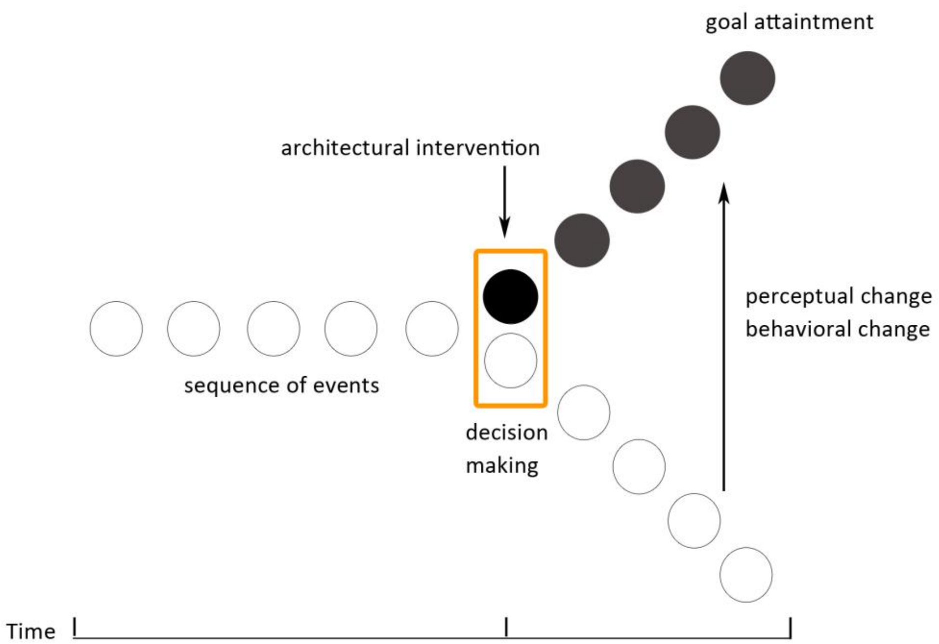

Figure 5.28. Goal Achievement by Directing User

<Source: Adapted from Maria Lorena Lehman, (2017), Adaptive Sensory Environments: An Introduction>

Furthermore, capturing the user's facial expressions (Figure 5.29) with gesture recognition, people's needs and requirements can detect easily and meet in real-time. Imagine that, all students in a classroom distracted from the lesson because of light quality and the ambient intelligence can detect this through their gestures or size of pupils and could propose the most appropriate solution such as on light or more complex solution.

Figure 5.29. Facial Expressions

<Source: Ross P. Holder and Jules R. Tapamo, (2017), Improved gradient local ternary patterns for facial expression recognition>

The idea of detecting people and analyzing their gestures have been already used in different industries. (Figure 5.30.) Companies such as Toyota are developing sleep detectors to increase safety.[143] Furthermore, in some shopping malls or cinemas, people satisfaction is already defined with gesture-recognition, so it could be used also for a museum, classroom or arrangement of a gallery.

Areas	Applications
Information Security	Access security (OS, data bases) Data privacy (e.g. medical records) User authentication (trading, on line banking)
Access management	Secure access authentication (restricted facilities) Permission based systems Access log or audit trails
Biometrics	Person identification (national IDs, Passports, voter registrations, driver licenses) Automated identity verification (border controls)
Law Enforcement	Video surveillance Suspect identification Suspect tracking (investigation) Simulated aging Forensic Reconstruction of faces from remains
Personal security	Home video surveillance systems Expression interpretation (driver monitoring system)
Entertainment - Leisure	Home video game systems Photo camera applications

Table 5.30. Applications of Face-Recognition

<Source: Ion Marqués, (2010), Face Recognition Algorithms>

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143 Marqués I., (2010), Face Recognition Algorithms, Universidad del Pais Vasco, p. 5

Main Source: MassyK.,(2008), "toyota develops eyelid-monitoring system". Cnet reviews

Deep Learning Algorithms for User Detection

As mentioned before, a DL algorithm could manage face/gesture recognition, pose estimation and activity recognition tasks while learning in real-time with high accuracy rate and speed rather then traditional models. Convolutional Neural Networks(CNNs) are mostly used for defining a person body, face and gesture recognition, which could show one's mood through gestures. Furthermore, Recurrent Networks could be used for recognition users' voice patterns according to their sound.

If the process is detailed, after reading human behavior, mood and emotion with the help of sensory tool, the input data could be classified as labeled or unlabeled data. Then, the consistent deep learning algorithm could be applied. While labeled input data use mostly supervised learning mechanism, unlabeled input data use mostly unsupervised learning mechanism.

If a CNN computation process is declared in detail with an example identification as shown in Figure 5.31 and Figure 5.32, firstly, there should be created a database, which contains images of users. If there is a need for identifying usual users of a space, frontal, lateral and backward images of each user could be labeled in a dataset and introduced to the intelligent system. After the system trains with this database to an adequate level, it can begin to identify the inhabitants easily. While classifying the users according to their ages or body forms, the dataset should be labeled in a different way.

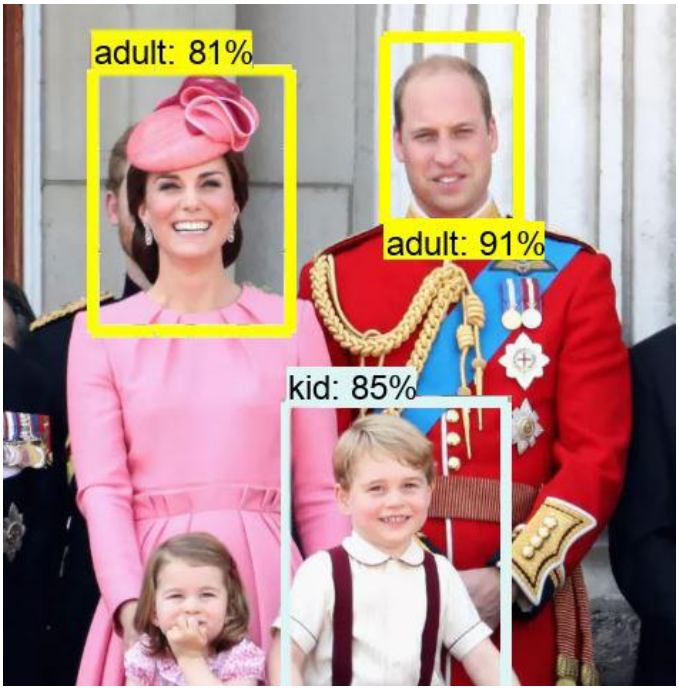

Figure 5.31 Identification the Royal Family, produced by the author

<Photo Source: 21 June 2018 < https://www.businessinsider.com/> >

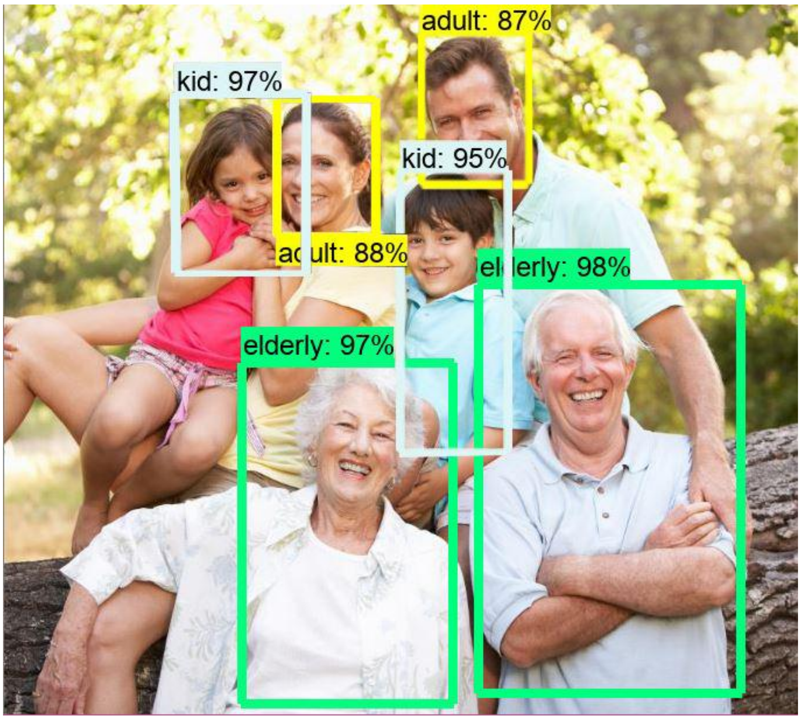

Figure 5.32. Identification an Extended Family, produced by the author

<Photo Source: 21 June 2018 , https://www.pinterest.com/>

Recognition of User Behaviors

An intelligent environment with embedded intelligence could recognize user activities in real-time with the help of sensory tools such as cameras, motion sensors and also pressure-sensitive floor tiles. Furthermore, in some environments such as galleries, museums or schools, user activity could be classified as individual or group activity through their body positions or their weights.

As each user has a different personality with individual mental and physical capability the use of space changes according to different ranges of age groups and their genders. Hence, each group creates its own specific behavioral pattern in an environment as shown in Figure 5.33.

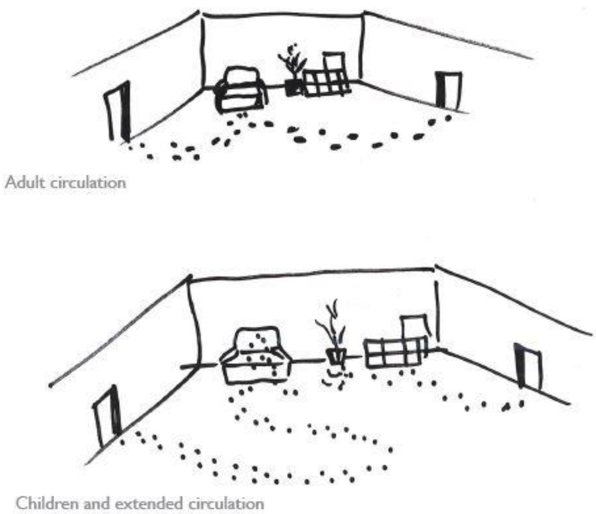

Figure 5.33. The Difference Between the Adult and Children Use of the Space

<Source: Kayan Ç., (2011), Neuro-Architecture>

The used space of the user can gain the personality while interacting them. As an example of it, an ambient intelligence captures the daily routine of a person and change itself hour by hour, even minutes by minutes according to this routine. Therefore, it can learn the habits of a human, such as studying, working, sleeping, even cleaning habits, in time and response them in accordance with the user needs and goals. To explain more, if an ambient intelligence captures the habits of a human while working, it can organize itself for achieving the goal of being an effective working environment through providing the required privacy, changing lighting and the structure of working environment or eliminating distracting materials such as closing windows and so on. In common spaces, there could be a need for the optimization of the goals/requirements of users for a consistent solution.

Deep Learning Algorithms for Detection User Behaviors

An interactive interface could learn with each feedback loops in interpretation process of computation. In interpretation process, Deep learning algorithms could provide to learn through unsupervised learning from gathered environmental inputs like cookies. They could extract the behavioral patterns of users. The algorithm trains with time because the data is unlabeled and uses unsupervised learning due to extracting pattern from unlabeled data. Hence, an interaction interface has the potential of estimating the next activity of a human while observing them in time.

Recently, studies on activity recognition of people are very common in the computational sciences. Most of them use the wearable sensors or smartphone sensors as sensory tools and used LSTM or the other type of RNNs as deep learning algorithms.

Figure 5.34. The Activity Recognition

<Source: Guillaume Chevalier, Human Activity Recognition>

<https://github.com/guillaume-chevalier/>

One example of them is produced by using TensorFlow[144] (Figure 5.34) on the smartphone sensor dataset and LSTM is used for computation process of classifying the movement amongst six categories: walking, walking up stairs, walking down stairs, sitting, standing and laying. [145]

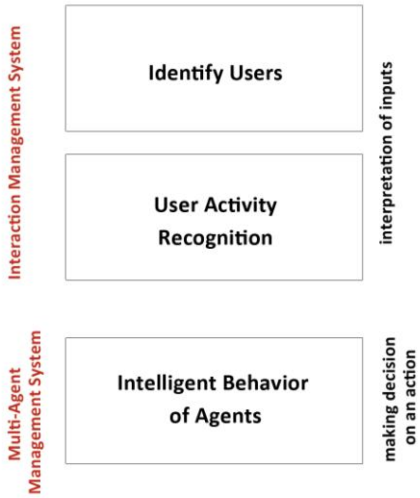

Figure 5.35. Computation Processes in Interaction Interface

To conclude, after identifying the space its own users and recognizing their activities, an interactive interface could manage to interact with its users more effectively. Furthermore, thanks to Multi-Agent Management System, the interface could direct its users to achieve their needs and goals while changing its physical and mental conditions with its dynamic property (Figure 5.35.).

5.2.3. Possible Scenarios of Interaction Interface

The general framework of proposed interaction interface can be formed by architect while considering the mutual relationship between user and space, and also the range of affection of dynamic behaviors on the mental and physical conditions of user and space. Therefore, an architect should define input and also output parameters. Input

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[144] An open-source software library for high performance numerical computation

< https://www.tensorflow.org/>

[145] LSTMs for Human Activity Recognition, (2018, August 10) retrieved from <https://github.com/guillaume-chevalier/LSTM-Human-Activity-Recognition>

parameters as motivation for the dynamism of the interaction interface could define according to the expectations from a space. As an example, the motivation parameters of the proposed interface could be light, temperature and air quality for the well-being of the users in space. As another example, the motivation parameters of the proposed interface could be again light and body temperature but for kinesthetic learning of the children through dynamic walls in this case. Covering both of them, the proposed wall system could move in micro-level for achieving the goal of kinesthetic learning of users while moving in macro-level for the well-being of users.

Some possible scenarios could be presented to lead the future works of the proposed interaction interface. In some cases, a working environment needs to be used for different purposes at different times. The dynamic change of the space according to these purposes could be defined with macro-level dynamism of interaction interface. The interaction interface can process and change itself step by step as follows:

1. First, the sensors of the interaction interface should collect the motion data input for the evaluation of behavioral patterns of users with deep learning algorithms.

2. After learning the pattern of uses, the interaction interface could move its dynamic wall system for dividing or combining spaces according to the goals/expectations.

From the micro-level perspective, if the proposed wall system is programming for the purpose of micro-level uses of staff, the proposed wall system can process and change itself step by step as follows:

1. First, the visual data of the staff should be given to the system for learning the staff of working environment.

2. The visual sensors of the interaction interface such as cameras can identify each staff after learning from a visual dataset.

3. The robotic agents or actuator agents of the interaction interface could move in micro-level according to each staff for providing to the needs such as working as a screen or writing board and so on while considering specific physical and mental conditions of each staff.

4. In a different case, the interaction interface could detect the number of staff in a space and could change its light quality or spatial quality according to the number of staff.

Hence, the main objectives of the interaction interface should be well-devised by the architect according to the needs or expectations of users and space while considering in mutual perspective of interactive communication. Furthermore, as mentioned above, the outputs of the interaction interface also should be well-designed for consistent intelligent dynamic behaviors of the interaction interface.

CHAPTER 6

CONCLUSION

Today, many varied type of dynamic architecture approaches are appeared in the field of architecture following the improvements in AI. Each of them concerns more or less the same issue that is designing a building for smart and sustainable living. Furthermore, the improvements in the field of dynamic architecture have been continued in the way of AI. Hence, after a deep researching on current dynamic architecture approaches, this thesis proposed a new dynamic architectural approach, which try to integrate and improve today's main dynamic architecture approaches.(Figure 6.1)

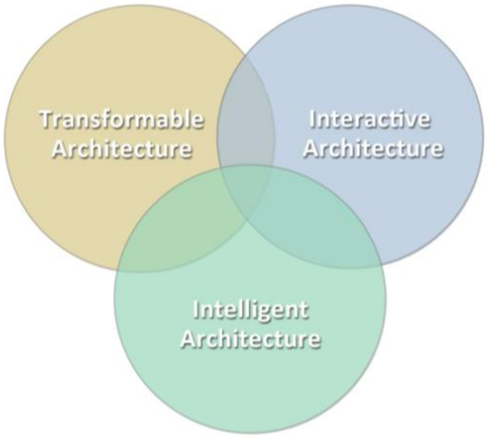

Figure 6.1 Intersection of Dynamic Architecture Approaches

The proposed conceptual model of dynamic architecture is developed benefitting from the latest improvement in AI. Hence, a dynamic environment is constructed with the properties having sensation, interpretation, decision-making and finally action as shown in Figure 6.2.

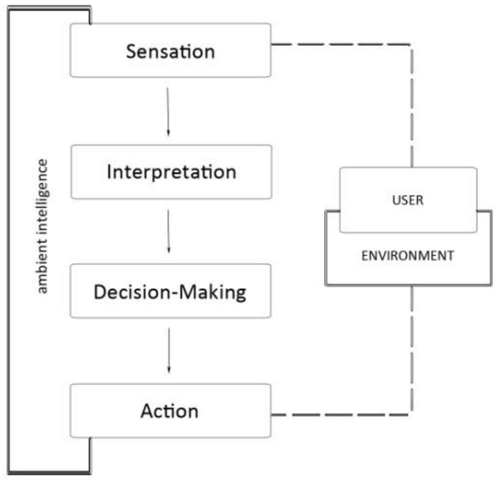

Figure 6.2. The Abilities of an Proposed AI

The proposed model contains an interactive interface for achieving the goal of being a dynamic, intelligent and also interactive. For this purpose the interactive interface should be designed considering a vary of requirements. The main requirements of the proposed interactive wall could be classified as follows:

- Conceptual Requirements: Interactive and dynamic behaviors of a space and their affects on user and environment could be devised by an architect for the conceptual framework.

- Functional Requirements: Meeting functional needs and goals of the users could be devised by an architect also for the functional framework.

- Physical and Technical Requirements: This type of model construction requires a collaberative study with engineering and architects due to the fact that on one hand it requires system analysis, on the other hand it requires devising architectural components and their configurations.

- Mathematical Requirements: The model intelligence and cognition could be managed by the mathematical algorithms using within the system computation mechanisms.

While the latest technological and computational advancements facilitate the solve problems of control mechanisms, a multi-agent dynamic system approach , which could be defined as the combination of swarm intelligence and multi-agent system, is used for the control mechanism of the proposed model. The advantages side of the multi-agent dynamic system is being hybridized control system rather than being a cenralized or decentralized control system. But, it has also disadvantages sides:

- Complexity

- Computational cost

- Sensitivity to loss of certain agents

- Communication delays between the commander agent and the other agents, and feasibility concerns regarding processing of local information by a central control unit, etc. in a possible central control scheme. [146]

Furthermore, while defining the cognition of the space, deep learning algorithms are used for the interaction management system mechanism. The sensation of an ambient intelligence should be in real-time. Because of its speed and accuracy rates, in the computation step, deep learning algorithms are mostly suitable according to other algorithms for real-time interactions. Hence, the system could identify its users and their activities, deep learning algorithms have an impressive potential of improving intelligent-interactive building study.

With an interactive interface, which could be able to change its own user needs and goals charactheristically, dynamic architectural environments could gain a new meaning for the future understanding of the building while adding to the life of human with its own personality and cognition.

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[146] Gazi V., Fidan B., op. cit. p.85

REFERENCES

Alcalá R., Benítez J.M., Casillas J., Cordón O., Pérez R., (2003), Fuzzy Control of HVAC Systems Optimized by Genetic Algorithms, Applied Intelligence, v.18 n.2, p.155-177, March-April 2003

Augusto J.C., (2007), Ambient Intelligence: the Confluence of Ubiquitous/ Pervasive Computing and Artificial Intelligence, Springer London, pp 213–234. Intelligent Computing Everywhere

Ataman O., Rogers J., (2006), Toward New Wall Systems: Lighter, Stronger, Versatile, University of Illinois at Urbana Champaign, School of Architecture

Beesley P., (2006), Responsive Architectures: Subtle Technologies

Bertoldi K., Vitelli V., Christensen V. and Hecke M., (2017), Flexible mechanical metamaterials

Callaghan V. and Clarke G, (1999), Multi-agent architecture for intelligent building sensing and control

Clements-Croome D., (2014), Intelligent Buildings: An Introduction, p.3

Clements-Croome D.,(Eds.), (2004), Intelligent buildings: design,management and operation, Information Technology,Communications and Artificial Intelligence in Intelligent Buildings

Clements-Croome D., Davies G., (2014), Bringing Intelligence to Buildings, Intelligent Buildings: An Introduction, p.15

Dougherty B.O., Arbib M.A., (2013), The evolution of neuroscience for architecture: introducing the special issue, Intelligent Buildings International

Dounis A. I., Caraiscos C., (2009), Advanced control systems engineering for energy and comfort management in a building environment—A review.

Renewable and Sustainable Energy Reviews, 13(6-7), 1246-1261. doi: 10.1016/j.rser.2008.09.015

Dwyer T., Kimpian J., Tang L.C.M., (2013), Building and virtual information modelling in intelligent buildings, The Journal of Intelligent Buildings

Elkhayat Y.O., (2014), Interactive Movement in Kinetic Architecture, Faculty of Engineering, Tanta University

Eng K., Bäbler A., Bernardet U., Blanchard M., Costa1 M., Delbrück T., Douglas R., Hepp K., Klein D., Manzolli1 J., Mintz M., Roth F., Rutishauser U., Wassermann K.,M Whatley A., Wittmann A., Wyss R. , Verschure P., (2003), Ada-Intelligent Space: An artificial creature for the Swiss Expo.02, Proceedings of the 2003 IEEE/RSJ International Conference on Robotics and Automation (ICRA 2003), Taipei, Taiwan, September 2003

Fox, M. A., Yeh B. P., (2010), Intelligent Kinetic Systems, Massachustts Institute of Technology, Department of Architecture

Fox M. (Ed.), (2009), Interactive Architecture: Adaptive World

Fu L., (1994), Neural Networks in Computer Intelligence,University of Florida, Gainesvil

Gazi V. and Fidan B., (2007), Coordination and Control of Multi-Agent Dynamic Systems: Models and Approaches

Goldberg, (1989), Genetic algorithms in search, optimization, and machine learning

Goodfellow I., Bengio Y., and Courville A., (2016), Deep Learning, The MIT Press, Cambridge, MA, USA

Hagras H., Callaghan V., Colley M., Clarke G., (2003), A hierarchical fuzzy–genetic multi-agent architecture for intelligent buildings online learning, adaptation and control

He, X., Xu, S., (2007), Process Neural Networks, Zhejiiang University, China

Hongqing F., Chen H., (2014), Recognizing Human Activity in Smart Home Using Deep Learning Algorithm

Hotta K., Hotta A. (2016), The Implementation of Programmable Architecture: Wireless Interaction with Dynamic Structure, Living Systems and Micro-Utopias: Towards Continuous Designing, Proceedings of the 21st International Conference of the Association for Computer-Aided Architectural Design Research in Asia CAADRIA 2016, 291–299, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

Jaskiewicz T. , (2010), (In:)forming Interactive Architectural Systems, Case of the xMAiA Meta-model

Khaldi B., Cherif F., (2015), An Overview of Swarm Robotics: Swarm Intelligence Applied to Multi-robotics

Kolarevic B., (2015), Building Dynamics: Exploring Architecture of Change

Kronenburg R., (2007), Flexible: architecture that responds to change, Laurence King, United Kingdom

L. Bus¸oniu, B. De Schutter, and R. Babuska, (2005),Learning and coordination in dynamic multiagent systems, Delft University

LeCun Y., Bengio Y., Hinton G., (2015), Deep Learning, Nature Vol 521

Lee J.H., Hashimoto H., (2001), Intelligent Space — concept and contents, Institute of Industrial Science, University of Tokyo, Komaba 4-6-1, Meguro-ku, Tokyo, Japan

Lehman M. L. , (2017), Adaptive Sensory Environments: An Introduction, pp. 71,170

Lehman M. L., (2011), How sensory design brings value to buildings and their occupants, Intelligent Buildings International, 3:1, 46-54

Marqués I., (2010), Face Recognition Algorithms, Universidad del Pais Vasco, pp. 5

Megahed N. A:, (2017),Understanding kinetic architecture: typology, classification, and design strategy, Architectural Engineering and Design Management, 2017 VOL. 13, NO. 2, 130–146

Miller, F.P.,Vandome , A.F., McBrewster , J. (Ed.), (2009), Competitive Intelligence, Business Intelligence

Miller P., (2016) ,Dynamical systems, attractors, and neural circuits, Volen National Center for Complex Systems, Brandeis University, Waltham, Massachusetts, 02454-9110, USA

Ong B.L., Pallasmaa J., (2013), Beyond Environmental Comfort, p.91

Oosterhuis K, Xia X., Sam E.J., (2007), Interactive Architecture

Orhon A. V., (2016), Adaptive Building Shells, p. 558

Overvelde J. T. B. , Weaver J.C., Hoberman C. & Bertoldi1K., (2017), Rational design of reconfigurable prismatic architected materials

Pan C, Jeng T.,(2010), A Robotic and Kinetic Design for Interactive Architecture, SICE Annual Conference 2010 August 18-21, 2010, The Grand Hotel, Taipei, Taiwan

Perlovsky, L.I., 2006, 'Toward physics of the mind: concepts, emotions, consciousness, and symbols', Physics of Life Reviews 3, 23–55.

Poole D.L., Mackworth A.K., (2010), Foundations of Computational Agents

Prakash, P. (2013). Building automtaion for enhanced energy and operational efficiency. Texas: Texas Instruments

Rudofsky, B.,(1964), Architecture without Architects, Univ of New Mexico Press, Mexico.

Sharples S. & Callaghan V. & Graham C., (1999), Multi-agent architecture for intelligent building sensing and control. Sensor Review - SENS REV. 19. 135-140

Sierra, E., García-Martínez, R., Hossian, A., Britos, P. and Balbuena, E., 2006, 'Providing intelligent user-adapted control strategies in building environments', Research in Computing Science Journal 19, 235–241.

Soteris A. Kalogirou (2009) Artificial Neural Networks and Genetic Algorithms in Energy Applications in Buildings, Advances in Building Energy Research, 3:1, 83-119, pp.90

Stephenson, D.G. and Mitalas, G.P., (1971), 'Calculation of heat conduction transfer functions for multilayer slabs', ASHRAE Transactions 77(2), 117–126

Tani, A., Kawamura, H. and Ryu, S. 1998, 'Intelligent fuzzy optimal control of building structures', Engineering Structures 20(3), 184–192.

Tamke M., Nicholas P. and Zwierzycki M., (2018), Machine learning for architectural design: Practices and infrastructure, International Journal of Architectural Computing 2018, Vol. 16(2) 123–143

Tuyls K. and Weiss G., (2012), Multiagent Learning: Basics, Challenges, and Prospects

Voulodimos A., Doulamis N., Doulamis A., and Protopapadakis E., (2018), "Deep Learning for Computer Vision: A Brief Review," Computational Intelligence and Neuroscience, vol. 2018, Article ID 7068349

Xiaoshu L., Clements-Croome D., Viljanen M, (2009), Past, present and future mathematical models for buildings: Focus on intelligent buildings (Part 1), Intelligent Buildings International. 1. 23-38.

Xingui He, Shaohua Xu (2007), Process Neural Networks : Theory and Applications, Zhejiang University Press, p. 20

Yiannoudes S., (2016), Architecture and Adaptation, From Cybernetics to Tangible Computing

Zadeh, L.A., (1965), 'Fuzzy sets', Information and Control 8(3), 338–353.

Zou, J. , Han Y., So S. ,edited by David J. Livingstone (2008),Artificial Neural Networks, Chapter 2;Overview of Artificial Neural Networks,p. 17

Wang, S. (2010). Intelligent Buildings and Building Automation. New York: Spon Press.

Wiener N., (1961), Cybernetics: or Control and Communication in the animal and the machine