The Animated Work Environment: A Vision for Working Life in a Digital Society

Henrique Houayek
Clemson University, hde@clemson.edu

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THE ANIMATED WORK ENVIRONMENT:
A VISION FOR WORKING LIFE IN A DIGITAL SOCIETY

A Dissertation
Presented to
The Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy in
Planning, Design and the Built Environment

by
Henrique Maria de Mendonça Houayek
May 2009

Accepted by:
Dr. Keith E. Green, School of Architecture, Committee Chair
Dr. Ian D. Walker, Electric and Computer Engineer
Dr. Ted Cavanagh, School of Architecture
ABSTRACT

Dramatic transformations in the nature, place and organization of working life due to increasing sophistication and access of information technologies in the United States suggest a redesign of the work environment as a socially and technologically responsive system occupying both home and office.

This thesis examines the process of creation of an “Animated Work Environment” [AWE]. A space in the scale of a cubicle envisioned as an environment-as-responsive-robot; an articulated, programmable interior accommodating a range of digital technologies across fluid assemblages of people working with both printed and digital materials in a variety of locations and settings, searching for a potential sensor based architecture interactivity.

As part of a transdisciplinary research team coming from the fields of Architecture, Robotics, Sociology and Human Factors Psychology, this thesis explores previous findings from surveys and ethnographic research with communities of highly educated individuals likely to be heavy users of digital technologies and translates it into the design of an animated workstation; an investigation of why, how and what computing possibilities and robotics can be translated into design patterns and possibilities for work environments, generating a new vision for working life in a digital society.

This thesis presents AWE’s iterative design process, which includes the design, prototype, construction and evaluation a fully operational workspace configurable in multiple work scenarios.
In response to these conditions, this thesis proposes to answer the following questions: (1) How can Intelligent Systems, Information Technology and Robotics become design elements in the creation of work environments? (2) How to design technological spaces supporting positive human interaction? (3) What are the metrics to evaluate such a project?

This work counterpoints a vision of architecture as static space, configured for pre-determinate functions, proposing instead the creation of a real-time responsive work environment. Presenting users with the possibility to morph and change its spatial configurations according to their needs and moods. A place where the physical environment becomes subject to constant manipulation, to accommodate different use modes and spatial interactions.
DEDICATION

To Paulo, Hugo and Kelly.
ACKNOWLEDGEMENTS

This thesis is for me an odyssey. It represents a journey to overcome multiple challenges; as it comes to an end, I would like to take a moment to mention some of the many people who provided support and inspiration along the way.

I would like to thank first Dr. Milton Feferman, my Brazilian mentor, for believing in my potential as an architecture student at Rio de Janeiro, encouraging and recommending me to Clemson’s PhD program.

I would like to thank all my committee members for their support during all the progress. I am truly indebted to Dr. Keith E. Green, my dedicated advisor and professor for his patience, help and invaluable comments.

My acknowledgements to all members of the AWE research, for their work, effort, and imagination, for believing in a vision for working life in a digital society.

To all friends, colleagues, professors, and students who supported me here at Clemson University. To Lauren Sandy for helping me with the language issues, and a special thanks to Eduardo Cervo and Danielle Rossi.
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CHAPTER ONE

INTRODUCTION

How do we coordinate the variable, physically based analog past with the programmed, chip-driven digital present? How do we bring vanished mechanisms into our midst again so they can provide substance to the thinner formats of virtuality, thoughtful alternatives to the automated logic of cybernetics? How can we encourage the cognitive – not just commercial – potential of liquid software, virtual hardware, and sensor-based interactivity?

Barbara Maria Stafford; Devices of Wonder, p:01

The network of increasingly powerful and inexpensive personal computing devices is revolutionizing many aspects of human existence, connecting individuals’ world-wide and making accessible to them vast amounts of information and opportunities. This increasingly digital society is nevertheless characterized by a person, the single user, facing a computer screen, accessing digital information within a static physical environment. While more and more people are engaged in cyberspace, they nevertheless continue to find utility and value in physical artifacts, materials and tools; and they also need and desire close human collaboration in complex working and leisure activities unfolding in a single physical space. For example, ethnographic studies (BONDARENKO 2005, SELLEN 2002) have shown that people performing complex, creative tasks vigorously resist the “paperless office” and find that paper affords many functions—such as annotation, reconfigurability, organizing information spatially, and shifting between storage, imminent use and active use—that computer tools do not perform as well.
1.1 From Things-To-Do to Things-That-Think

Since 1994, microprocessors’ have outnumbered humans on Earth, a ratio that is growing exponentially. (FIGURE 1.1) Microprocessors are found not only in computers but also increasingly in things we carry, drive, wear, in places we visit, and artifacts we use to work. (MCCULLOUGH 2004: 5) We once interacted with static thing of stone, metal, wood – objects with a very stable physical attribute. Recently things are becoming less and less “something to do something else” and increasingly “something that does something.” (MANZINI 1989: 40) A ‘communicative cause’¹ in a Heideggerian conception of object, things now acquire interactive properties: they now sense and communicate. As the MIT media lab explores – the future of digitally augmented objects and environments – “Things-That-Think”, ²

---

¹ Heidegger describes the use and craft of technology in four causes Causa Materialis: the materials by which the production is necessary, Causa Formalis: the shape which the product takes, Causa Finalis: for what is the product been made for, and last Causa Efficens: the effect of the product over the user. More details can be found in his seminal work “Question Concerning Technology”

² http://ttt.media.mit.edu/
If things think, than the aesthetic of things no longer needs to correspond to its form or physical attributes, they become instead the physical manifestation of relationships, “less matter, less energy, more information.” (MANZINI 1989: 39)

‘Things-that-think’ defy the classical concept of function and use; they become ambiguous, a part of a social and cultural system of interactions. They develop a new sensorial capacity. “We perceive, act, learn, and know through the mechanically, electronically, and otherwise extended bodies that we construct and reconstruct for ourselves. And, as we are beginning to see, there is no limit to this extension.” (MITCHELL 2003: 38)

1.2 Critical Analysis and Opportunities

The format of the man-machine relationship is the goal of humanism through machines. The question is not one of rationalism versus vitality, nor the degree of rationalism, nor the castration of spirit by technique. The concern is to avoid dehumanizing a process whose aim is definitively humanization.


What are the social and physical implications of these changes in the use of IT and digital graphic interfaces for working life? As information technology (IT) continues to progress, are we as a society going to continue to allow it to permeate our everyday lives? If we do, what will change? Moreover what are the implications to the design of work environments? These are the questions of the Animated Work Environment (AWE). One major transformation that continues to occur is the movement of work from the traditional “office” to the home. Technology has made it easier to work from home; and
with both, the increase in commute times and changes in family dynamics, the ability to receive digital information at home or to have a conference meeting through web cams online, may help alleviate some of the day-to-day stress that would otherwise be felt.

However, if we are “reachable” at every moment of the day, through wireless communication devices, laptop computers and Wi-Fi Internet connections, are we ever able to escape from work? With the ubiquity of wireless devices, it comes as no surprise that the average workweek no longer fits into the 9-to-5 mold, with the traditional implication that you work “at the” office, and live “at” home.

Instead we find ourselves living in a 24/7 global economy. Employees can no longer go on vacation without the expectation that they will be checking their email. Sick days no longer exist because there “must be something you can do while lying in bed.” Before we were tied to our desks by heavy machines and wires; now we can be anywhere doing anything and still be “at work.” On the other hand, these new technologies also make it possible for a child to send her homework to a parent to review while the parent is at work, or for the parent at work to call a child on her cell phone. In this case technology brings the home to work. Despite the increasing change of work patterns and technology evolution, work environments remain very conservative, they remain (1) Fixed for individual use; (2) Fixed for specific tasks; (3) Concerned with how to interact with virtual documents; (4) Neglectful of the contributions of Computer Science
Working with sociological insights on the affordances of technologies such as the Internet and cell phones, the challenge for the AWE project is to take the increasingly permeable boundaries between work and home and transform them from intrusions to accommodations. Andrew Lang states that for design:

“Fundamental to this rethink is to break away from the idea of the work space as an individual desk occupied full time from nine-to-five every day. As soon as the basic stereotype of the office design is questioned, then a new world of work patterns and office design becomes a real possibility” (LANG 1997: 34)

Working life in a digital society presents new challenges which include: working at once with digital and printed matter; collaborative computing across groups of workers; tasks distributed across space and time; and a dynamic workforce which is telecommuting, short-term, part-time, outsourced and grow older in increasing numbers. In response to these tendencies, the AWE project was developed. Envisioned as an
intelligent, programmable, physical space with embedded IT supporting working life in a digital society.

There are critical opportunities here: (A) architecture and technology might evolve hand in hand; (B) Architecture and technology might extend our senses and our spatial possibilities; and (C) Architecture and technology might support sociable interactions. “As more and more automaton enters all aspects of our lives” argues Donald Norman, designers need “to keep people engaged, to provide the correct amount of natural, environmental information so that people can take advantage of automation to free themselves to do other things, yet can take control when condition requires it.” (NORMAN 2007:152)

Such projects require not so much a change in technology, but a change in how and for what it is employed.

“These systems and networks not only are the ‘connective tissues and the circulatory system’ of modern economy, they also constrain and enable social and cultural formations…these…are all mediated by technology. We cannot responsibly escape this condition of modernity, and we need ways to confront it constructively.” (MISA 2003:4)

More than a naïve prediction, there are great and exciting possibilities which come from explorations in architecture and technologies. Design becomes both a responsibility and the consequence of a critical analysis of both social conditions and technological possibilities.
1.3 Research Questions

This thesis consists of two key aspects: first, the design process related to theoretical foundations which are multidisciplinary; and second, issues of performance related to design evaluation and metrics.

The research questions are:

I. How can Intelligent Systems, Information Technology and Robotics become design elements in the creation of physical work environments?

II. How to design technological spaces supporting positive human interaction?

III. What are the metrics to evaluate such a project?

These three questions explore an uncertain and difficult repertoire on how to incorporate intelligent robotics in the field of architecture, a challenge that unites design paradigms and the interaction between different disciplines.

The AWE project is an exploratory research investigation which searches for answers concerning how people work/interact/interface, and how much this influences architectural design outcomes.

1.4 Animated Work Environment: an Overview

For the Animated Work Environment (AWE), I responded to the research questions by designing a workstation to meet two key goals: (1) mixed-media use — allowing users to use a range of digital and analog displays such as monitors, paper, whiteboards, and corkboards; and (2) user-programmability (reconfigurability) —
allowing users to flexibly rearrange their physical environment, to meet changing task demands. AWE (FIGURE 1.3) offers an alternative vision to single and group work environments, and also mobile and desktop computers. (FIGURE 1.4) A user-programmable, physical environment with embedded Information Technology (IT), AWE supports users engaged in both routine and complex tasks requiring non-trivial combinations of digital and physical artifacts, materials and tools, and peer-to-peer collaboration in one physical space.

FIGURE 1.3 Animated Work Environment in a Collaborating Composing mode. (Author)

AWE is viewed as part of a growing tendency within IT research concerned with various interconnected issues related to working life, including the use of multiple displays organizing mixed-media, managing healthcare records; and, more broadly, practices frequently defined as Computer-Supported Collaborative Work (CSCW). In particular, AWE builds on prior research in intelligent environments such as the IBM BLUE SPACE and ROOMWARE. These informative and compelling precedents, however, focus not on robotics or physically reprogrammable spaces but mostly on
collections of computer displays, whiteboards and novel peripherals to create electronic meeting rooms. Technologically, AWE sits instead at the interface between computer technology, architectural design and robotics, where the physical environment (including display surfaces for paper) is also subject to manipulation.

Figure 1.4 Computers and computing has become ubiquitous and is now more than the interaction with one static screen. What is the future of the specialized user? (Author)

AWE is envisioned to improve user experience, both “at work” and “at home,” by adapting to work and leisure activities that employ digital and analog tools and documents. The AWE concept is inspired in part by William Mitchell’s vision offered in “e-topia”. Mitchell believes that “the building of the near future will function more and more like large computers” and that “our buildings will become…robots for living in” (MITCHELL 2000: 69)

We implemented the design goals of user-programmability and reconfigurability by giving AWE the capability for robotic movement. The robotic dimension of the AWE project is enabled, in part, by recent progress in the exploration of continuum structures to create active physical environments. This has been explored by the group of Kas Oosterhuis at the Technical University of Delft, which has constructed programmable,
flexible “play” spaces framed by continuum structures. The physical AWE prototype presented here is more complex, featuring novel continuum surfaces supporting and enhancing purposeful human activities in an increasingly digital society. AWE has two key physical elements: the user-programmable robotic system equipped with an array of embedded sensors and IT peripherals, and a collection of three horizontal work-surfaces which are reconfigurable.

This thesis considers the conceptual and technical foundations underlying the development of the Animated Work Environment project. The following chapter, chapter two, will explore the conceptual foundations with a consideration of work, and work environments across history. It provides a discussion on the evolution of the office space typology; how it changes with the digital revolution, and what does this theoretical background suggests about new directions in work environments. Moreover, it discusses technological approaches to intelligent environments presenting theoretical examples.

Chapter three presents the conceptual theory for an Architectural Robotics underlying notions of openness, responsiveness and performance – concepts anticipated by visionary architects and philosophers of the 1960’s. The chapter concludes by identifying current possibilities in robotic architecture.

Chapter four presents the AWE research, beginning with my role. The chapter follows with a consideration of pertinent social science research and how it guides AWE’s design. The chapter presents different concepts for an Architectural Robotics; namely the three alternative AWE prototypes and, significantly, the design, construction
and testing of prototype-3. This chapter concludes with the workstation usability evaluation and its findings.

Chapter five presents a critical reflection on how technologies are manifested in the AWE project. The chapter provides a discussion on levels of success in such projects. The chapter concludes with a discussion on how robotics redefines architecture and architecture education.

Chapter six concludes this thesis with a summary of contributions and future directions for the research.
CHAPTER TWO

CONCEPTUAL FOUNDATIONS

2.1 Working Life and Work Environments Across History

Office design is at a turning point. For many decades… office users have tended to be passive. Vendors of office have concentrated on perfecting the delivery of the office buildings – obviously at most profit, least risk, and maximum convenience for themselves. During most of this period, from 1920 to 1970, office organizations, office technology, and the expectations of office workers remained more or less constant…the electronic office cannot be accommodated as easily as the old office technology. Information Technology is too potent and destabilizing as agent of change for that.

Francis Duffy; The Responsible Work-Place: The Redesign of Work and Offices, p:08

The interaction between humans and artifacts does not take place in a vacuum. Rather it always occurs in an historical, social context and in a physical environment. For a long period of time we have learned to create artifacts to survive and compensate our weakness, secondly to express all our potentiality. This chapter presents an evolution of work environments across history from a social and technological perspective. It sets the conceptual foundations for what the AWE project is and aims.

This research understands that work environments, as they are today, do not represent a final state, but are constantly evolving. Different fields collide, bringing new forms of social connection and technological developments. There are still innumerable fields to be explored, incalculable hypotheses to emerge and technologies to develop. Technological production is constantly changing and evolving.
2.1.1 Modern Work Environments: From Industrial Revolution To WWII

Characterized by significant changes occasioned by the culmination of technological developments, new energy sources, new organizations of power and a change in division of labor, the industrial revolution is a turning point in history with significant changes in the American and European landscape, and most significantly, the way labor and their environments are designed.

In labor organizations before the industrial revolution times, there were, in the process of production, fewer separations between conception, control and execution. Techniques of production were developed in a profound relationship between craftsman, the qualities of the materials, and labor. (MANZINI 1989: 50) This relationship changed in the Industrial Revolution, where the rational, the economical and the scientific dominated labor and their respective work environments. The assembly line dissects complicated processes into simple elements, ordered in a series of discrete yet related activities, setting the belief of progress under the faith of serial production.

Work environments were molded primarily under Fredrick Taylor’s ideal of efficiency and Henry Ford’s concept of labor. Taylorism and Fordism generated the notion of work and its environments as a production system based on fixed time, fixed space and standardized behavior. The separation between control, management, conception and execution developed work environments based on uniformity and standardization, single task performance, regulation, rigidity of tasks, and functional spatial specialization. (HARVEY 1990: 178)
Work environments became representations of these tendencies, designed for highly segmented, hierarchical divided spaces, in a routine mechanical task for a traceable, observable and contained worker. At this period, the consensus was that machines do not adapt to humans, instead man adapts to machines in order to accomplish a very specific set of tasks.

This mechanistic tendency to organize the production and its workers into a very rational working process was not only accepted but glorified by modern designers. In early twenty century, prominent architects followed and praised this tendency: in Europe, Walter Gropius designed the Fagus Factory, Peter Behrens the AEG Turbine, Le Corbusier the Manufacture Duval; In the US, Frank Lloyd Wright designed the Johnson Wax Building and the Larking Building (FIGURE: 2.1). Despite their architectural qualities, these projects followed precisely the Fordist/Taylorist model of work, a pragmatic/functionalist approach to production and labor for highly segmented, linearly reproduced separation of equal workspaces.

FIGURE 2.1 Larkin Building designed by Frank Lloyd Wright, 1904 Buffalo, NY. Left: Outside View of building; Center: View of the core office area; Right: Left wing office area. Despite the interesting arrangement of volumes with a double height internal core. Its Internal arrangements follow a production method based on uniformity and standardization, single task performance, regulation, rigidity of tasks, and functional spatial specialization. (Source: Frank Lloyd Wright Foundation; http://www.franklloydwright.org/Home.html)
2.1.2 Post-WWII Work Environments

Workstations are different, new technologies have proliferated throughout the space; the lightning and furniture are entirely updated. Yet when one compares in detail the pattern on the space and use the core assumptions of the occupancy of the space over time, very little has changed. The changes are cosmetic and superficial.

Andrew Lang; New Patterns of Work: the Design of the Office p: 30

In considering changes in work life in the US from pre to post WWII, sociologists recognize the passage from an economy of production to one of services the most significant. According to sociologist Domenico de Masi, 1956 is the year of change when in the US “the number of workers in the tertiary (service) sector [have] outnumbered the sum of workers in the industrial and agricultural sectors.” ³(DE MASI 2000: 84) Work system are now organized into five axial principles: (1) the change from production of goods, to production of services, (2) the increasing importance of liberal professionals and technicians overcoming the worker class; (3) the central role of the theoretical knowledge; (4) problems related to technical developments became so powerful and important that they could not be administrated anymore by isolated individuals and last; (5) the development of intelligent machines that are capable of replacing man not only in functions which required physical effort, but also intellectual effort. (DE MASI 2000: 111)

³ Translated from Portuguese by Henrique Houayek

Despite the increasing change in the American working system, office environments were still being designed according to a ‘factory’ model, taking into consideration work characterized as fixed-space, time-specific and task-oriented.
Moreover, the majority of architects facing the issue of designing spaces accommodating work narrowed the problems to building skeleton and skin. The belief in technology is reflected in an architecture that prioritizes material and formal possibilities over its employees. “The Modern Movement, for example, rarely confronted in detail the relationship between the building and the activities of its occupants,” argues Andrew Lang; “this lack of concern was exacerbated by the separation of the interior design of the office from its structural design, the architect merely providing flexible space for subsequent interior design. (LANG 1997: 30)

Significant examples of such design can be seen in projects by, New York based firm Skidmore Owings & Merrill: the Lever House (1952), the Connecticut General Life Insurance Company (1957), the Pepsi-Cola Building (1960). (FIGURE 2.2) Projects, which carried corporate image with an undefined interior space, a fusion between geometrical alignments and visual homogeneity. Workspaces are to be filled by the standardized rational lines of desks. These projects became the role model for a generation to come.

2.1.3 Moving From Skin to Core: The Burolandschaft

In the sixties the conception of a Taylorist building begins to change with the arrival of two innovative ideas. In 1959 the West German Quickbonner team developed the concept of Burolandschaft, the ‘Office Landscape’. At first glance what appears like a gesture of random settings of furniture in a heterogeneous (FIGURE 2.3), creative chaos, is actually designed to address efficiency by improving, in a large deep space, different work groups in constant interaction and visual communication. “The idea of the office environment was evolving away from a static building shell towards the concept of a self-regulating structural grid within which working groups grow and change.” (LANG 1997: 39)

FIGURE 2.3 Left: Quickbonner Diagram of continuous working areas. Right: Quickbonner plan for office landscape. (Source: ABALOS and HERREROS; Tower Office: From Modernist Theory to Contemporary Practice. MIT, 2003: 199/200)
Over the evolution of the building, its disposition of furniture “began to be used to define [space] within deep open plans and to respond to the needs of small autonomous work groups”. (LANG 1997: 39) The Burolandschaft defies the notion of static work environments; instead it presents the beginnings of highly nomadic work patterns where the space is designed for constant movement and interaction between workers.

2.1.4 Playful Furniture: Herman Miller’s Action Office

By the 1960’s it became clear that the traditional concept of office building could not solve the emergent issues regarding work life. Different visions for furniture and interior design emerged as a way to improve working and life conditions. Significant examples of furniture design emerging in this period can be seen in the work of designers such as Charles and Ray Eames with their light weight furniture system; Joe Colombo and his experimental habitats and furniture; Gio Ponti’s experimental houses, such as the Adatta with its movable panels and lightweight adaptable furniture; Hennessey and Papanek’s design for a Nomadic Furniture. Common to all of these is the advantage of serial production system, introducing new ways of conceiving interior spaces through design. These designers envisioned an interactive space in a gradable, movable and playful mode where the architecture and its interior could be disassembled, and restructured, a plug-n’-play of diverse interactive elements instead of firmitas.

At the time the Herman Miller company was engaged in exploring new possibilities for work furniture design. It released in 1964 a ‘kit’ that changed the way office interiors were developed: the Herman Miller Action Office. (FIGURE 2.4)
Designed by Jack Kelley and Robert Propst, *Action Office* used the idea of plug-n’-play in a kit comprised of different sets of panels corresponding to a variety of office layouts and work modes organized in different configurations. Its designers recognized the conflicts between privacy and communication in work life, and mobile changeable working needs. “The problem of change was solved by giving management responsibility to the user. The furniture itself began to take place on some of the sub-divisional functions of the building shell and allowed designers to break away from the right angle of their layouts. The hardware was modular so that the worker could select and adapt different components according to changing needs.” (LANG 1997: 38)

![FIGURE 2.4: Left; Kit of parts containing different pieces. Right: a contemporary Herman Miller built Action Office; (Font: Herman Miller official website www.hermanmiller.com)](image)

### 2.1.5 1980’s: The Digital Revolutions

“The disassociation of the building from the interior life of the office only began to break down and therefore to demand a greater reconciliation between the building shell, its environmental services, and the settings appropriate to the life of the organization, with its revolutionary impact of information technology (IT) in the 1980s. The pressure of change of organizations and the continuing development of IT through the 1990s has meant that complex demands by users continue to require radical and holistic approaches by architects and designers to the office environment.

Andrew Lang; New Patterns of Work: the Design of the Office p.33
In the sixties and seventies, Gordon Moore’s predictions became reality: the research on transistors and microprocessors evolved to a point where computers shrank in scale and increased their power exponentially. The possibility of a personal computer became reality. Xerox, Apple and IBM, among others, started to dominate the market, releasing commercially successful personal computers, (The IBM 5150, the Apple Lisa and Apple Macintosh, the Atari ST, Compaq Deskpro 386), changing radically the way contemporary life and work environments existed. The integration of the PC into contemporary life turns attention to software design, neglecting the development of physical work environment design. Software alone promised to solve all contemporary issues regarding controlling, communication, service and organization in work environments.

Should computers and Information Technology, generally not also precipitate a complete change in the way office environments are organized? As William Mitchell says: “Buildings and parts of buildings must… be related not only to their natural and urban contexts, but also to their cyberspace settings.” (MITCHELL 1995: 104) The myth of the paperless office was born; and with that, architectural design loses relevance. Fortunately for designers, the paperless dimension was never more than a myth (BONDARENKO & JANSSEN 2005); physical work environments were inseparable from new technological improvements, new design ideas, and the constant interaction between the digital and the analog.
2.1.6 New Directions in Work Environments

Changing the workplaces mean continuous reappraisal of the way we work, the spaces we occupy, the technology we require and the ways in which services are delivered. For providers and theirs architects, the challenge is to avoid conventional solutions. Working simultaneously both physically and virtually is certain to result in workplaces that are very different from the norm.

John Worthington; Reinventing the Workplace p:07

Beginning in the mid-1990’s, public awareness and use of the World Wide Web use grew and the Internet increasingly became a widely used medium for communication and information exchange. Web information resources are continuously expanding. High-speed broadband connections were increasingly available to individuals within the United States. This not only increased connection speed, but also increased the amount of time spent on the Internet and the range of activities engaged while online.

The result of this change for work environments was that “the big monolithic company yields to districts and apparatus” (DE MASI 1999: 139) business model is not only big companies, but now smaller, more Ad hoc enterprises, “for a great number of dependents it becomes technically possible to work with terminals in its own house, or in organized intermediary units, this determinates a disruption of the productive space.”

(Translated from Portuguese edition by Henrique Houayek) Now working life could acquire a different spatial aspect, the development of these new technologies presented a condition where the individual workplace – ‘one seat per person’ – is challenged.

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4 Translated from Portuguese edition by Henrique Houayek
Andrew Lang establishes six emerging characteristics for new modes of working life in office space. These are: (1) Highly mobile and nomadic work patterns; (2) the use of multiple shared group work settings; (3) Diverse task-based space; (4) Extend and erratic periods of working; (5) Varied patterns of sometimes high-density space use; (6) More shared and temporary ownership of settings within the office combining with teleworking and home-working. (LANG 1997: 33) Complementing these characteristics is the digital arsenal that now we carry. Computers went from filling a big room, to a luggable suitcase, to a briefcase and eventually our pockets, extending our senses and possibilities, and allowing us to work and connect to multiple people over long-distances anywhere in the world.

“Wireless networks, portable electronic devices, and online work environments now allow information workers to move freely from location to location as needs, desires, and circumstances demanded…discovered that they just needed a cell phone and a laptop to operate effectively at their nominal workplaces…Anyplace was now a potentially workplace. And this condition would only intensify as the technology of nomadic developed and proliferated.” (MITCHELL 2003: 153)

New directions in work environments demand more versatile, hospitable, accommodating spaces to serve diverse purposes as required – an architecture less about responding to rigid programs, and more about creating supported, flexible, reconfigurable, spatial events.
2.2 Technological Approaches to Intelligent Environments

2.2.1 Intelligent Environments

2.2.1.1 Gordon Pask and the New Architecture Machines

It seems to me that the notion of machine that was current in the course of the Industrial Revolution – and which we might have inherited – is a notion, essentially, of a machine without goal, it had no goal ‘of’, it had a goal ‘for’. And this gradually developed into the notion of machines with goal ‘of’, like thermostats, which I might begin to object to because they might compete with me. Now we’ve got the notion of a machine with an underspecific goal, the system that evolves. This is a new notion nothing like the notion of machines that was current in the Industrial Revolution, absolutely nothing like it. It is, if you like, a much more biological notion, maybe I’m wrong to call such a thing a machine; I gave that label to it because I like to realize things as artifacts, but you might not call the system a machine, you might call it something else.

Gordon Pask in Husman Haque; The Architectural Relevance of Gordon Pask

A computer scientist with a degree in psychology Gordon Pask’s work was novel in his search for possibilities of real time interactions between man and the objects in its surroundings. His work derives from Cybernetics and System Theory, which considers the built environment as not something finished or static, instead, an interconnected, cognitive, communicative learning system, involving mechanical and organic matters. It represents a shift from understanding the built environment as something represented by grids to become holistic, a network of different relationships.

His work on Conversation Theory and Architecture derives from an organic perspective, which attempted to present buildings as self-organizing systems working on the principles of feedback, homeostasis and control. Buildings leave their state as background to become a language-oriented system, designed to present certain levels of
sensing and interpretation and react to people experiencing the space, Gordon Pask work proposes ways to embed different levels of intelligence into the built environment.

Colloquy of Mobiles (FIGURE 2.5) is an installation set in the 1968 exhibition ‘Cybernetic Serendipity’ at the Institute of Contemporary Arts, London – one of the first exhibition which presented a series of works by artists exploring early connections between computers, art and architecture. Colloquy of Mobiles is an experiment where actions from both the installation and people interaction in it lead to impacts on the environment leading than to sensing and further modifications of actions. It is a suspended collection of mechanical artifacts capable of moving and rotating, it is divided into two parts, female and male, the first reacts to different interactions to the environment directing beams of light to moving elements, the second uses a combination of servos and mirrors to reflect light. They are both in a constant interactive dance looking for ways to connect they media. Moreover, when unattended – meaning no
human interaction - the Colloquy moves and dances looking for different positions between lights and mirrors, like a kinetic moving sculpture.

2.2.1.2 Nicholas Negroponte and the Architecture Machine Group

Architect and computer scientist Nicholas Negroponte employed, within his laboratory at M.I.T., advances in IT to explore the interactivity and spatial responsiveness of architecture. Investigations by Negroponte’s Architecture Machine Group (which later became the Media Lab) yielded a series of insights which redefined both architecture and computing. The research objective was to create, in Negroponte’s words, “ecosystems capable of intelligent responses….” (NEGROPONTE 1975: 129) An emerging technology, the computer environment became an important metaphor for the workings of the natural environment: the natural environment viewed as, itself, an “Intelligent System.”

Negroponte, who studied and followed most of Gordon Pask’s work, recognized the computer as an agent which understands and reacts to its users. He was interested in the “rather singular goal of making the built environment responsive to me and to you, individually.” As elaborated by Negroponte:

Computers have the potential for assuring a responsiveness, individuality, and excitement in all aspects of living, to a degree hitherto unseen. For the first time in history, for example, we can see the possibility of everybody having the opportunity to live in a man-made environment that responds to and is “meaningful” for him or her. (NEGROPONTE 1975: 129)

For Negroponte and his Architecture Machine Group, the computer served as a participatory, reflexive design tool which transformed space, light and sound. Walls
moved by the command of the inhabitants. Color and shape changed according to inhabitants’ actions. Architecture became a responsive, open machine.

SEEK (FIGURE 2.6), a project developed by the Architecture Machine Group, is an architectural work which senses and responds actively to conditions within an existing environment. Its purpose is to understand users' environmental behavior and from it, create different spatial conditions extracted from new responsive patterns. Physically, SEEK is a giant rodent cage filled with five hundred metal-plated cubes distributed in a formal manner. Rodents were selected as the “inhabitants” of this “architecture” for their tendency to actively structure and modify their habitats. In SEEK, whenever an “inhabitant” moved a cube, the space changed configuration. A computer meanwhile recognized the developing spatial pattern of the cubes as organized by the inhabitants. Intelligently, the computer sent signals to a magnetic arm hanging from the ceiling to move and adjust individual cubes, thereby formalizing (i.e. cleaning-up or ordering) the environment configured by the rodents. The configuration of the environment is continuously responsive to the inhabitants’ activities and formalized by the computer system. Negroponte was not just testing the possibilities of computer technology; he envisioned more a complete spatial freedom in architecture afforded by Intelligent Systems which sense the actions of inhabitants and alter, responsively, their local environments.
FIGURE 2.6 Nicholas Negroponte’s SEEK cage, the environments shape is the result of a computer understanding of the inhabitants’ behavior (source: Nicholas Negroponte, *Soft Architecture Machines*, Cambridge, MA: The MIT Press, 1975, 46-47)

2.2.2 Intelligent Work Environments

“The machine is not intelligent: the intelligence is in the mind of the designer”.
Donald Norman; *The Design of Future Things* p: 13

Most definitions for machine intelligence to date are based on a metaphor for human intelligence. Machine-man communication is the major issue regarding intelligent interactions. “Designers of advance technology are proud of the ‘communication capabilities’ they have built into their systems. But a closer analysis shows this to be a misnomer: there is no communication, none of the back-and-forth discussion that characterizes true dialogue. Instead, we have two monologues.” (NORMAN 2007: 04)

The AWE project and its supporting references follow a theoretical tendency which considers that intelligence in machines cannot and should not be compared to human intelligence. “For decades, scientists in the field of artificial intelligence have
Artificial intelligence conceives thinking as a kind of machinery and uses computers as models for the mind; however, Jeff Hawkins rejects this statement, presenting a perspective where “brains and computers are fundamentally different things.” (HAWKINS 2004:05) Moreover the basic attribute to intelligence is that “Intelligence and understanding started as a memory system that fed predictions into a sensory stream. These predictions are the essence of understanding. To know something means that you can make [complex] predictions about it. (HAWKINS 2004: 104) Something, which still today, machines cannot be designed to do. “There is no way a machine has sufficient knowledge of all the factors that go into human decision making.” (NORMAN 2007: 09)

Nicholas Negroponte and Kas Oosterhuis argue for a different perspective which helps define the field of Intelligent Environments and Architectural-Robotics. Negroponte states that a machine responding with intelligence is one designed to “discern changes in meaning brought about changes in the context.” (NEGROPONTE 1970: 01) “Intelligence is not necessarily aware of itself as being intelligent, Intelligence can very well emerge from swarming relatively stupid components”. Says Oosterhuis, and: “together they perform as something complex, which humans may interpret as intelligent.” (OOSTERHUIS 2005)

Intelligence in environments will consider elements in architecture that have the ability to some extent respond intelligently to user needs. Four aspects will define the
notion of intelligent architecture: (1) System which senses and receives information, processes and analyses. (2) Output that reacts to the information received. (3) How this information is collected (4) time it takes to respond. Real time responsiveness is an important part of the idea of machine intelligence.

2.2.2.1 Contemporary Computing Theory: Soft Computing Vs. Peripheral Interaction

Beginning in the 1980s, computer scientist Mark Weiser, then of Xerox PARC, introduced a new perspective on responsive environments, investigating how IT can be embedded in our surroundings. What has become a field of its own, “Ubiquitous Computing” was Weiser’s term for environments made responsive by means of embedded IT.5 Weiser envisioned “Hundreds of computers per room,” (WEISER 1991) all of these physically small and acting, recognizing and responding to each room’s inhabitants. For Weiser, the most important aspect of the productive interaction between people and computers is when computers become invisible, acting beyond our recognition in the environment; it becomes independent of the operator, an autonomous technology. As Weiser states, “the most profound technologies are those that disappear: they weave themselves into the fabric of everyday life until they are indistinguishable from it.” (WEISER 1991) The computer becomes actively integral to the everyday lives of people within their surroundings.

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5 Ubiquitous computing was developed by Mark Weiser at the Computer Science Laboratory at Xerox PARC in his own words "Ubiquitous computing names the third wave in computing, just now beginning. First were mainframes, each shared by lots of people. Now we are in the personal computing era, person and machine staring uneasily at each other across the desktop. Next comes ubiquitous computing, or the age of calm technology, when technology recedes into the background of our lives.” Mark Weiser, “Ubiquitous Computing”, http://sandbox.xerox.com/ubicomp/
While Weiser argues that the future of computing is in an invisible path where information is exchanged in a unconscious level, an opposite perspective is put forth by Steve Shafer from Microsoft; his Vision Technology Group intends to bring intelligence to environments by increasing connections between different electronic devices. “We express the belief that intelligence implies an ability to work in cooperation with mobile devices” say Shaffer “any intelligent environment or ubiquitous computing system must allow for growth and improvement of its constituent parts, or it will die.” (SHAFER 1999) Outside peripherals will be the major point to create intelligent interaction, calling it “Appropriate Computing”.

FIGURE 2.7 Peripheral interactions as a way to augment sensorial and computing possibilities. (Source: Shaffer, S. Ten Dimensions of Ubiquitous Computing; http://www.research.microsoft.com/easyliving)
2.2.2.2 Two Intelligent Work Environments: IBM BlueSpace and Roomware

The IBM BlueSpace is a research developed to present a workspace solution which could be reproduced throughout office buildings with the same ease as cubicles, addressing many of the common complaints, associated with the standard office cubicle. The project intents to combine existing technologies along with technologies which are just emerging; from the research environment in a novel way to resolve common issues in knowledge workers.

The IBM BlueSpace (FIGURE 2.8) is a cubicle incorporating a set of different sensors and peripherals to improve work possibilities. It contains sensors capable of measuring ambient light, temperature, humidity, and noise level. Additionally, the desk chair is equipped with a pressure sensor connected to a wireless micro-controller, which detects users presence in the chair. An active badge and reader are used for presence detection and identification. A set of environmental actuators integrated into BlueSpace include various illuminating and signaling lights, as well as an electronic system composed of a fan and a heat panel, designed to provide adjustable heat and airflow to desks in open-plan offices. The module is installed at the bottom of the main worktable.

There are three flat panel displays in the space. The first, the Office-Front, is integrated into the Threshold component; the two other are mounted on articulating arms. They are focused to work in both individual and collaborating modes. Also there is a projection system capable of project images into any surface in the workspace. The images are corrected for oblique projection distortion.
FIGURE 2.8 IBM BlueSpace physical prototype
(Source: IMB BlueSpace website http://www.research.ibm.com/bluespace/)

Different from the IBM BlueSpace, which is concerned to support users in a static work environment, the Roomware project wishes to support users’ in highly mobile and nomadic work patterns by the use of single or multiple shared group work settings in a diverse task-based space to work with digital information. The Roomware project is part of a concept of Cooperative Buildings (STREITZ 1998) to develop different elements in a space which serves to improve cooperation and communication, employing active, attentive, and adaptive components. “In the future, work and cooperation in organizations will be characterized by a degree of dynamics, flexibility, and mobility” Says Norbert Streitz. (STREITZ 1998: 06)

The project is divided into four main interactive pieces under different modes to engage in creative work: (FIGURE 2.9) (1) DynaWall: an interactive digital wall measuring 4.50 meter width by 1.10 meter height it wishes to create the impression that you are really writing and interacting with a wall or wallpaper. The surface is touch-sensitive so it can be interact on it with fingers or with a normal pen (no electronics
needed). (2) InteracTable: a table display measuring 65 cm by 115 cm and a diameter of 130 cm. Embedded with touch sensitive surface it provides additional software to shuffling and rotating digital information across the surface so that they can orient themselves automatically. (3) CommChairs: Mobile chairs with built-in or attached slate computers. Having the dimensions of a basic office chair represents a new type of furniture combining the mobility of armchairs with high-end information technology. Has an integrated pen based computer built into the swing-up desk. It allows workers to communicate and to share digital information with other Roomware appliances. (4) ConnecTables: Mobile, small desk appliance, which allows users to work in parallel on an ad-hoc connection creating, shared digital workspaces. Measuring 70 cm height by a square 45 cm planar section it contains a touch-sensitive digital surface so it can be interact on it with fingers or with a normal pen.

All Roomware appliances are capable Bluetooth communication with pads and smart phones to share and store digital files.

FIGURE 2.9: Roomware project; Left: Environment containing all DynaWall, InteracTable, CommChairs and ConneCTables showing different affordances; Right: detail of CommChairs. (Source: Project Roomware website; http://www.roomwareproject.org/)
2.2.3 Robotic Environments

2.2.3.1 Kas Oosterhuis and the Muscle Body

In recent years within the practice and research of architecture, the Hyperbody Research Group (HRG) has been developing new aspects for interactive robotic environments. HRG’s Kas Oosterhuis redefines the architectural design process as an interaction of 3-D modeling software, computer coding, peer-to-peer communication networking, and mass-customization. In the HRG, rather than having architects generate the forms of architecture in traditional ways, computers scripted by the architects analyze and evaluate the particular conditions within the local environmental, and the information collected, in turn, generates customized architectural works of unique elements responsive to these conditions. This process of architectural production, writes Oosterhuis, produces “an endless variety of different building elements, visually rich and complex,” (OOSTERHUIS 2004) which may themselves morph in response to environmental conditions, form follows feedback.

In their robotic works, HRG embeds data-driven programmable elements capable of changing the physical configuration of the ensemble in response to information gathered from inhabitants’ interaction with their surroundings. A real-time responsive environment is actualized by way of Weiser’s “hundreds of computers per room,” each computer capable of exchanging information and altering the physical form and structure of architecture.

HRG’s “MuscleBody” (FIGURE 2.10) proposes a kinetic, interactive architecture of this kind. Its space is constituted by a continuous, stretchable fabric which
accommodates seventy-six pneumatic Festo muscles – its programmable structure. Each muscle is embedded with sensors capable of recognizing the actions of each inhabitant.

When a person interacts with the interior of this architecture, embedded sensors recognize this human activity; the information of the action is transmitted to a computer; and the computer injects or removes air from the environment’s muscles, stretching or contracting the muscles to alter the environment’s form in response to the information received.


The Muscle Body’s intelligent system has the autonomy to determine, for each human action, if the physical response should act fast or slow and if it should vibrate or shake, using parameters for behavior like frequency, duration, interval and weight. This architecture is subject to real-time, constant change. Oosterhuis makes a parallel between Negroponte’s early research and his own when he characterizes projects like the Muscle

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6 Festo muscles are pneumatic artificial muscles that are contracted or extended by pressurized air. As advantages they are light-weight very strong structures depending on pressure or state of inflation (see: www.festo.com)
Body as a “paradigm of programming soft design machines.” (OOSTERHUIS 2004) A new way to conceive architecture, the experimental works of the HRG is generated by human engagement, the environment, technology, new materials and complex geometry.

2.2.3.2 dECOI and the Aegis Hyposurface

Aegis Hyposurface is a responsive robotic surface designed by French firm dECOI to react and change shape according to environmental stimuli. Initially this project was developed for an interactive art work competition at the Birmingham Hippodrome Theatre foyer, latter exhibit at the CeBIT technology Fair in Hannovver in 2001. This robotic wall contains one thousand pistons and actuators covering over sixty-four square meters of surface. According to Marc Goulthorpe, its main designer, the Aegis Hyposurface is an “attempt to put people in a physically reciprocal relationship with the environment, a dynamically interactive architecture attuned to their activity.” (GOULTHORPE 2004)

Its actuators move pneumatic fifty centimeters pistons changing the metal triangles angle, creating the dynamic topography. The topography reacts and changes shape according to subtle differences in light and color, and to a participants’ stimuli. Once an inhabitant enters in contact with the Hyposurface, its sensors detect levels of movement and light, a script expanding users movement to the wall, creating a new relationship architecture and user. The inhabitants’ movement is passed to the wall and acquires an environmental dimension. The Hyposurface reacts to multiple users creating topographic patterns, which considers the integration between objects and space.
Fig 2.11 Aegis Hyposurface changing its topographical qualities as the result of user stimuli.
“Our buildings will become...more like us. We will continually interact
with them, and increasingly think of them as robots for living in.”
William Mitchell; *E-Topia* p: 59

Recent advances in Intelligent Systems have made some number of anti-modern,
counter-cultural visions of the 1960’s and 1970’s realizable in architectural works.
Intelligent Systems are those that gather information from the environment, act in
response to this information, and learn from this gathering-actuating process to better
perform their functions. Intelligent Systems include computer software programs,
sensors, motors, and movable components – any element of Information Technology [IT]
which has the capacity to read or react either through direct commands or sensors
precisely to given information about the environment. Embedded in architectural works
at various scales, Intelligent Systems allow architecture to become open, responsive and
performative – qualities ascribed to artistic works in seminar philosophical works of the
1960s and 1970s like Umberto Eco’s *The Open Work* and Roland Barthes’ *Death of the
Author*.

In architecture of the same period, the Italian group *Superstudio* envisioned new
living possibilities enacted across a spatial continuum, affording creation, performance
and interaction. This spatial continuum was described by Superstudio as “a genuine space
of involvement (a stage for continuous performance or, in other words, a place for
happenings, a place for the be-in) by the agency of the design products we place in it.”

(NATALINI et al. 1967) *Fun Palace* by Cedric Price and the *Living City* by British group *Archigram* integrates Superstudio’s sense of the “be-in” with their own “pop” fascination with technology, resulting in concepts for a performatively, “plug-n-play,” biologically inspired Architectural Robotics. These new architectural possibilities were translated by Renzo Piano and Richard Rogers to the actualized Beaubourg museum, with some critical compromises, in Paris. As Nicholas Negroponte’s predicts, the creation of “ecosystems capable of intelligent responses…. Buildings that can grow and upgrade themselves, that open like flowers in fine weather and clamp down before the storm, that seeks to delight as well as serve you.”(NEGROPONTE 1977: 129)

This tendency to transgress the limits of conventional architecture extends to the work of Bernard Tschumi and his efforts to establish new codes for spaces and events. “Architecture,” for Tschumi, “ceases to be the backdrop for actions, …becoming the action itself.” (TSCHUMI 1996: 149) “Architecture-as-action” calls to question the classical distinction between subject and object, suggesting that the environment is a space of constant flow between subjects and objects, a space characterized as ephemeral, tangible or intangible. The architecture that Tschumi strains to realize might be an example of the technological "plane," which philosophers Deleuze and Guattari define as…

…not simply made of formed substances, aluminum, plastic, electric wire, etc., nor of organizing forms, program, prototypes, etc., but of a totality (ensemble) of unformed matters which present no more than degrees of intensity (resistance, conductibility, heating, stretching, speed or slowness, induction, transduction . . . and diagrammatic functions which only present differential equations. (DELEUZE AND GUATTARI 1984: 07-19)
An advanced and increasingly accessible means for rendering architecture a “technological plane.”

Advances in Intelligent Systems research, and the increasing accessibility of IT to non-technical users, has made it possible to realize architectural works of advanced complexity which defy the modern tenants of program, permanence, timelessness and authorship. The focus of this architectural strategy is on multiple, interacting, physical elements rather than on static physical forms preconceived by the designer. While embedded computer displays and LED’s have been a strong, recent trend in the application of Intelligent Systems to architecture, the concern of this chapter is the particular, rarer, emerging instances of Architectural Robotics where physical mass, rather than digital bits, are subjected to movement and reconfiguration. Such robotic works of architecture include the “Muscle Body,” a responsive environment comprised of computer-controlled bladders, developed by the Hyperbody Research Group, lead by Kas Oosterhuis at the Technical University of Delft, and the “Animated Work Environment” [AWE], a dynamically reconfigurable, intelligent environment supporting working life, developed by this research and their collaborators at Clemson University. These are two current and formative examples of an Architectural Robotics exhibiting, as Oosterhuis explains, the capacity to “reconfigure itself and produce complexity and unpredictability in real time.” (OOSTERHUIS 2004) “Architectural robotics is concerned with the development of a new kind of machine for living, a mechanical structural system that will allow the spaces of a building to be reconfigured in minutes, and entire neighborhoods to grow and recede in days.” (WELLER AND DO 2007)
Architectural works like the Muscle Body and AWE have the potential to alter the course of architecture and architectural education by placing in motion, figuratively and literally, the very stability of architecture. The architect of such architecture is not the sole master of it but in this instance, a member of a transdisciplinary team, following closely the working paradigm of engineering and scientific research than that of the “genius-architect.” Such a re-conceptualization of the role of the architect and the definition of architecture is compelled, today, by the complex concerns of living in an increasingly digital society. Spaces are determined not through program, but through programming. The resulting work becomes less a “pure” work of architecture and more a hybrid of architecture and other concerns, guided partly by the architect. But what does this architecture look like? How does it behave? And, is it faithful to the visionary thinking that pre-dated it?

3.1 “Open” Architecture

*The comprehension and interpretation of a form can be achieved only... by repossessing the form in movement and not in static contemplation.*

Umberto Eco; *The Open Work* p:163

An Architectural Robotics can be described, foremost, as architecture in motion. The possibility of an “open” architecture, a form “in movement,” has its origins in the concepts of “freedom” and “openness” raised by the philosophical and technological formation of 1960’s culture. In the sixties, the counter-culture movement and the
electronic, media revolution reshaped the way architecture was presented. An anti-modernist stance, openness and freedom in creative practices came as a response to the existing rationalism and determinism of a mass-produced, machine-age society. This new paradigm was not only defined by Roland Barthes’ concept of the *Author’s Death* and Umberto Eco’s vision of the *Open Work*, but also, latter, by Gianni Vattimo’s *Weak Thought*,7 the *rhizome flow* of Deleuze and Guattari (DELEUZE AND GUATARI 1987) and, in architectural thinking, recapitulated in Manfredo Tafuri’s sense of the *form of formless*, (TAFURI 1974) and Ignasi Sola-Morales’ *weak architecture*. (SOLA-MORALES 1996: 57-72) For all these thinkers, the physical environment is an ambiguous form, shaped by the interaction – the performance – of human inhabitants in space.

While the technological means for creating responsive environments were introduced in the sixties, concrete ideas for a performative, intelligent architecture became achievable only with the aid of advanced and accessible computer hardware and software – a development only gaining ground in the later seventies and eighties. A “responsive environment” can be described as an environment capable of sensing and responding somehow to different human actions. This interaction is comprised of the input and output of information, and results in communication and physical changes in physical form and function in real-time.

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Intelligent environments responsive to dynamic, environmental conditions were not conceivable before the Modern movement’s aspiration towards a mechanical, technological ideal. Primarily because the philosophical roots of Modernism were still based on rationalism and deterministic thought, modern architecture prioritizes, to some degree, the designer’s knowledge over the user’s interaction with the environment. Function prevails over freedom. The house is a machine for living in, not a living machine, responsive to its inhabitants. While modernist architects achieved a few examples of mobility and flexibility through the environment – the brise soleil, movable furniture, non-structural walls, movable, pivoted, retractable plans – these design strategies cannot be considered responsive, as they still are exceptional states of a given standard. Manipulated by the user, these movable elements create only the illusion of freedom. The form of modern architecture reflected the designer’s vision and was not the result of a time-based interaction between inhabitants and the environment.

A modernist, deterministic view could not explain aspects of complex and ambiguous phenomenon such as human behavior, biological systems and weather conditions that were foci of investigations undertaken in the 1960s. As Charles Jenks observed:

In the sciences and in architecture, itself, a new way of thinking has indeed started. It stresses self-organizing systems rather than mechanical ones. It favors fractal forms, self-similar ones, over those that endlessly repeated. It looks to the notions of emergence complexity and chaos science more than to the linear, predictable and mechanistic science. (JENKS 2001: 01)
In the sixties began a concern with more complex and contradictory views of society and its culture, reconfiguring the way objects were designed, how the environment was manipulated, and how people interacted with things and each other. The definition of “object” was expanded to include aspects of its character outside its physicality. Technology ceased to be viewed as deterministic or instrumentalist, the means to an end, promising instead the possibility of enhancing the environment and achieving real-time responsiveness. As John McHale explained, “rather than man and his society being further enslaved by the machine process, he is potentially freed from his previous bondage as a muscle machine.” (MCHALE 1969: 47)

In *The Death of the Author*, Barthes wrote that a single creator of an artistic work is no longer possible. The multitude of cultures and symbols react on the object, altering its significance, rendering it open to judgment. Anyone can understand the work and use it in any way. The author plays one role in the realization of the full work, which is realized, as well, partly by its interpreters, its users; their will prevails over the work’s original form. The work is performative: what matters are the way people interact with it, the process by which people understand it. “The work ‘performs’ and not ‘me’” wrote Barthes. (BARTHES 1977: 143)

Umberto Eco understands this as “acts of conscious freedom” in *The Open Work*. (ECO 1989: 04) Recognizing the ambiguous nature of society, Eco suggests how artists, broadly defined, take advantage of uncertain situations to create objects capable of performing and adapting to different situations as needed or desired. Such artistic works can move or be moved, change or be changed. Their forms adapt according to a variety of
possibilities, different interactions, gaining significance by being engaged. “In fact,” wrote Eco, “the form of the work of art gains its aesthetic validity precisely in proportion to the number of different perspectives from which it can be viewed and understood.” (ECO 1989: 04)

Beginning in the sixties, the conventions of modernist architecture, itself inspired by classicism, were questioned. “A key slogan of 1968 is: imagination takes power” states Bernard Tschumi. (TSCHUMI 1996: 15) “Everything is Architecture” writes Hans Hollein. (HOLLEIN 1968 in OACKMAN 1993: 459) As part of this paradigm shift in architecture of the 1960s, an Architectural Robotics was anticipated in visionary works and investigations of Cedric Price, Archigram, Superstudio, the Piano and Rogers team, Gordon Pask and Nicholas Negroponte, among others; a consideration of these conceptual and investigative antecedents is essential to understanding current, applied work in the field. Nevertheless, while the architects of this earlier era sought to realize architectural works embedded with advanced technology, only with recent advances in IT and, specifically Intelligent Systems, has it become possible to realize an Architectural Robotics as open, responsive and performative as that which had earlier been envisioned.

3.2 The “Performative,” Anti-Architectural Object of 1960’s

Visionary 1960s works and concepts by architectural practitioners and researchers resonated with Eco’s recognition and investigation of the “fast dynamics and fluxes” of our living condition which “mark a radical shift in the relationship between artist and public.” This radical shift, for Eco, required “of the public a much greater degree of
Beginning in the sixties, Superstudio, the architecture group led by Adolfo Natalini and Cristiano Toraldo di Francia, envisioned a performative architecture where the physical form of the environment is the result of a dynamic, creative process shaped, at least partly, by the inhabitants. For Superstudio, the key is to “be-in”: the public is invited to “modify [the] time and space” of architecture and eliminate its “formal structures” towards creating a “free form work.” (NATALINI et al. 1967)

“One of the greatest weaknesses of our immediate urban architecture,” wrote Archigram’s Peter Cook, “is the inability to contain the fast-moving object as part of the total aesthetic.” (COOK et al. 1999: 29) What Cook calls the “fast-moving object” was the result of advances in technology and, significantly, the embedding of computer displays and robotics in architecture. An architecture of embedded IT offered two different possibilities: first, the environment as a “digital display,” where all or parts of the building’s skin and/or interior surfaces transmit moving words and images; second, architecture as a morphing, malleable, programmable environment, where physical elements of the building move and/or change form. The first possibility involves a change in surface image but not physical form – in a certain degree, a new model for architectural aesthetics and decoration; whereas, the second possibility involves a transformation of plan and/or shape and (potentially) programmatic use.

The Fun Palace (FIGURE 3.1) was one of the visionary works of this period which combined concepts of performance, responsiveness and cybernetics. The project
was the result of the collaboration between Architect Cedric Price and theater director Joan Littlewood – later project members include Gordon Pask, Buckminster Fuller and Yona Friedman. Littlewood played an important role conceptualizing the Fun Palace as she was the founder of the Manchester Theater of Action, an experimental stage group which utilized public engagement as part of the theatrical performance. The result of such collaboration was an architecture which acted as a responsive “open stage”.

Fun Palace’s interior was composed of changeable plans and walls, movable parts – pods, escalators, stages – these could be combined in numerous ways to enable and service a variety of use and spatial configurations, to be arranged mechanically by the architecture sensorial abilities – these abilities followed Gordon Pask Theory of Conversation. The Fun Palace was conceived as “an articulated, dynamic spatial shipyard designed to encourage users to be responsible for their entertainment, their learning and their space.” (SPILLER 2008: 50)

The Fun Palace propose a visionary statement of architecture for mass interaction and entertainment, Gordon Pask argued that the Fun Palace could “overcome restrictions in entertainment media such as cinema and television.” (SPILLER 2008: 50)
The architecture of the London-based Archigram follows from Eco’s concept of an “Open Work” and Superstudio’s manifesto of the “be-in” it also adds a computerized, robotic aesthetic. Archigram envisioned a total, mechanized architecture-as-city, a controllable responsive landscape. (FIGURE 3.2) For Archigram, “the central implication of the Plug-in-City is its openness.” (COOK et. al 1999: 29) The character of the Plug-in-City depends, as Cook elaborated, “upon situation as much as established form…. Each part would be exchangeable. Various ideas about automated shopping, and diagonalized movement combine with the office tower. (COOK et. al 1999: 38)
Archigram envisioned the Plug-in-City as a giant machine growing in the middle of an existing landscape, a project which would unite mobility and responsiveness. This Architectural Robotics incorporates the aesthetics of fictional spacecrafts sprouting giant, mechanical, flexible “tentacles.” Archigram’s intent was to afford buildings and cities the capacity to grow, adapt and change according to different human programs. Archigram did not accept the city body as it was, superimposing upon it their “living” body: a robotic city over a static city, a Living City, a Walking City (FIGURE 3.2), a Plug-in-City, an Instant-City – all these embodying the “openness” and “responsiveness” of a free society by means of robotics. Employing robotic elements, Archigram created “expandable buildings” within an “urban environment” that “can be programmed and structured for change.” (COOK et. al 1999: 36)
In its time, the work of both Cedric Price and Archigram remained conceptual, in part, due to the limited means and affordability of the technology required to realize it. Cedric Price and Archigram’s work are significant for testing the limits of the human imagination, for envisioning artificial landscapes of new and anticipated technologies that might impact human life in a productive, or at least compelling way, where “urban or architectural, or mechanical, or human mechanisms thrive … together.” (COOK et. al 1999: 38)

In the same historical moment, the Beaubourg Museum in Paris, designed by the young Richard Rogers and Renzo Piano, (FIGURE 3.3), is a physical realization of Archigram’s technologically-inspired quest for a new environmental “ideal” as well as Superstudio’s sought-after “openness.” For Kenneth Frampton, the Beaubourg Museum “represents the design approach of indeterminacy and optimum flexibility taken to extremes.” (FRAMPTON 1982: 285)

Situated in the middle of a historic Parisian zone, the Museum appears as a giant, mechanized image of monumentality expressed by technological elements of the high-tech aesthetic. In the competition proposal for the building, its robotic behavior was much more pronounced than the resultant construction. Several of the building’s interior elements (walls and floors) were conceived to move and, in some cases, morph; spaces generated by a mechanized changing process. The building’s exterior, a huge information wall included moving physical elements and computerized banners transmitting data. As realized, the exterior of the building openly expresses its steel frame and infrastructure, allowing the creation of large, open, interior plans, to be arranged mechanically. These mechanisms afforded changes in the configuration of the building’s plan, section and elevations. While only some of the building’s movable parts were realized in the building as constructed, this project suggests the possibilities of merging Architecture and Robotics within the historic city.

3.3 Current Possibilities in Architectural Robotics and Introducing the Animated Work Environment [AWE]

Today, advances in Intelligent Systems research and, the increasing accessibility of powerful IT tools, afford the realization of prototypical architectural designs characterized by Eco’s “Openness” and suggestive of Archigram’s robotic design. Dynamic time-based reconfigurations of the physical environment afforded by information exchange are not only feasible now but also are very likely to be, in the future, a significant way in which architects envision architecture.
More recently, architectural researchers William Mitchell and Malcolm McCullough have investigated responsive, intelligent environments: architectural works of embedded computer hardware and software which actively respond to local conditions as if they were “living entities.” Embedded IT, notably multiple computers and sensors, allow buildings to sense the presence and behavior of inhabitants and the presence and movement of virtual and real objects, resulting in responses and accommodations to local, dynamic conditions in support of human needs. As Mitchell writes, “Our buildings will become less like protozoa – static, non responsive – and more like us. We will continually interact with them, and increasingly think of them as robots for living in.” (MITCHELL 2000: 59) Individually, Mitchell and McCullough propose the embedding of real-time communicative sensors and actuators in architecture as a powerful means to forward the behavioral capacity, more than the aesthetic capacity, of architecture. For these two architects, architecture no longer needs to express the aesthetics of the machine, as prevalent in so much of 20th-century architecture; instead, architecture becomes responsive, performative and open for users’ interaction and needs.

Perhaps Bill Gates, in a recent *Scientific American*, sees beyond the possibilities of personal computers an environment enhanced by robotics: the next revolution in computing. In his words, “robotic devices will become a nearly ubiquitous part of our day-to-day lives.” At the start of the revolution, already well underway, “the pc will get up from the desktop,” writes Gates, “and allow us to see, hear, touch and manipulate objects….” (GATES 2006)
AWE is a workspace composed of a multi-panel, modular, articulated structure (FIGURE 3.4) capable of folding and reconfiguring its surface to match the needs and wants of different users. AWE allows users to alter their work experiences by redefining the physical environment. The movement of the surface is made by way of eight hinged panels rotating by means of eight electric motors. When activated, the actuators move one or more of the eight panels to create spatial configurations accommodating different group activities. Six major spatial configurations are programmed for AWE\(^8\) supporting: “Collaborating,” “Composing,” “Conference,” “Gaming,” “Lounging,” “Playing,” “Presenting” and “Viewing.” Each of these programmed spatial configurations has a pre-established form. As envisioned, each of the six standard configurations can then be “fine-tuned” by users operating touch sensors to accommodate the particular needs of individuals and their tasks.

\(^8\) Chapter 4 presents a detail description of AWE and its configurations
While the AWE prototype remains at the physical scale of a cubicle, it is not a stretch to imagine this AWE prototype extended to the physical scale of a large room or small building. Using the same specifications for AWE presented here, one can expand the area of each of AWE’s panel to a degree, both in vertical and horizontal plane, and combine multiple AWE workstations to create a programmable environment at the larger scale to include a meeting room, a bar or an information center (FIGURE 3.5). Every time one visits such an environment, the sectional condition of the environment could be entirely different, depending on any number of dynamic variables that may include: the number of people present in the environment, the weather, the vehicular traffic immediately outside the environment, and even the dynamic climbing and falling of the stock market. The AWE project promises to yield real insights into the potential of a totally responsive Architectural Robotics at various scales.
CHAPTER FOUR

THE ANIMATED WORK ENVIRONMENT

This chapter presents the design, prototyping, demonstration, and evaluation of the AWE project. The following images contain an evolution of the AWE design process; each phase represents a few weeks’ discussion and iterations. As design process, proposals were presented in our weekly meetings by me and discussed by all group members. Present regularly were the four discipline mentors: Dr. Keith E. Green (Architecture), Dr. Ian Walker (Electrical and Computer Engineer), Dr. James Witte (Social Sciences), Dr. Lee Gugerty (Psychology); also each field graduate students participating in different aspects of AWE. Every week I presented a series of different drawings, diagrams and concepts. Each presentation was followed by intense discussion regarding every aspect of the design. Each discipline collaborated with their technical and theoretical expertise. At the end of each meeting a list of design changes was developed. I would then change the drawings and present again as an iterative design cycle.

4.1 My Research Activities in the Animated Work Environment Project

For a project such as AWE, only a multidisciplinary research can make it become reality. Its process defies the boundaries of individual doctoral research and develops a research methodology, which connects the different disciplines involved. This work presented the challenge to unite such realms, a novel practice in academia, especially at

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9 Isaiah Dunlap (Architecture Master Student) Martha Kwoka (ECE Master Student), Jennifer Turchi (Sociology Master Student) latter replaced by James Rubinstein (Sociology Master Student), Joe Johnson (Mechanical Engineer Undergraduate Student) and Nathan Klein (Sociology Master Student).
the doctoral level. Few schools adopt such model and are the exception. A very successful model for this type of project is developed at both the MIT Media Lab\textsuperscript{10}, and at the \textit{Hyperbodies} research group at Delft University. These schools push the boundaries for design and education. Their doctoral program methodology was used to outline the way the AWE project works and to define the role of each student’s activity.

In the AWE project, my dissertation is here composed of my individual work which contributed to a series of peer-reviewed papers for which I’m in times the first author. While the AWE research is multidisciplinary, many of its activities were lead by me:

1) Designing concepts for the responsive robotic wall;

2) Designing and fabricating AWE’s vertical and horizontal work surfaces

3) Constructing the virtual (e.g. Simulated) and the physical AWE Prototype;

I also was a key investigator in the following:

a) Creating users’ working scenarios;

b) Participating in the creation of AWE’s six basic configurations;

c) Designing and conducting usability evaluations sessions.

\textsuperscript{10} The 2005 doctoral thesis at MIT: “Media Tables: An Extensible Method For Developing Multi-User Media Interaction Platforms For Shared Space” by Alexandra Mazalek guided the way this thesis was outlined. It had both William Mitchell and Joseph A. Paradiso, the first MIT Media Lab Director, the second director of the ‘Responsive Environments Group’ as thesis readers.
4.2 Today’s Workplaces And A Response: An Animated Work Environment

Three contemporary conditions compel the reconsideration of the workplace: firstly, society is becoming increasingly digital; secondly, the working population is expanding in range to include, in increasing numbers, older people, immigrants, and those working flexible schedules; and thirdly, the place of work now extends well beyond the confines of the office to include the home, the café, the car and the internet. New organizational strategies and tools are clearly required to satisfy the demands of working life, defined today by fluid, decentralized relations across a wide spectrum of people, machines and environments. The efforts of the project to design, prototype, demonstrate and evaluate a work environment for an increasingly digital society is inherently multi-disciplinary, spanning a number of areas of critical interest to Computer-Human-Interaction, including human-centered design and innovation, design research, and the social impact of technology.

FIGURE 4.1 - Left: Brian Alexander’s “Concept Work Station” – all design, no IT (Source: Paola Antonelli: Workspheres: Design and Contemporary Work Styles. MOMA 2001: 102)
FIGURE 4.2 - Right: UNC’s “Office of the Future” – all IT, no design. (Source: http://www.cs.unc.edu/)

A key goal for the AWE project is to explore the potential for improving the quality of the work experience, both “at work” and “at home,” by intelligently adapting
the physical environment. This project aims to bridge the divide between the work environments envisioned by Information Technology (IT) and those of Design (i.e. architectural, interior and furniture design) – the two fields most directly shaping today’s workplace.

While even the most recognized, forward thinking designers neglect to integrate IT into their work stations, IT investigators, meanwhile, neglect to consider the physical environment in developing IT applications to support work activities. This divide is epitomized by designer Brian Alexander’s whimsical “Concept Work Station” (FIGURE 4.1) from the Museum of Modern Art’s Worskpheres exhibition that treats IT as an appliance set upon, rather than integral to, the work station ensemble; and by an artist’s rendering of University of North Carolina’s “Office of the Future” (FIGURE 4.1) epitomizing the general failure of IT researchers to recognize the physical context as a means to intensify and expand the interaction of people and information technologies. The most promising efforts to envision a work environment responsive to today’s demands are IBM’s “Blue Space” and “Roomware”\(^{11}\). Both important steps towards integrating IT and Design. “Blue Space,” however, contains few and rather timid “smart” components and a narrow range of embedded IT peripherals, while ‘Roomware’ better in these respects, accommodates multiple users supporting a limited range of work activities.

In broad theoretical terms, the AWE is inspired less by these precedents than by the convergence of IT and the built environment posited by William Mitchell; that “The

\(^{11}\) Both described in detail in section 2.2.2.2

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building of the near future will function more and more like large computers”, and that “Our buildings will become…robots for living in” (MITCHELL 2000: 59). The AWE project also finds inspiration in the work of architect Kas Oosterhuis\textsuperscript{12} of the Technical University of Delft who is developing real-time configurability in programmable pavilions. Both visions suggest an evolutionary stage for architecture and represent a surprisingly small faction of interest by architectural researchers in programmable, physical environments.

4.3 Social Science Research and Findings for an Animated Wok Environment

4.3.1 Ethnographic Findings

This part focuses on the ethnographic research findings of the AWE project – from surveys and task analyses conducted by the social science investigators and, most important, how these findings informed AWE design concepts and its six physical configurations.

4.3.2 Phone and On-Line Surveys of Tech-Savvy Workers

The research team completed 400 phone surveys with individuals in two relatively affluent and technologically savvy communities, Cambridge, MA and Santa Monica, CA. Initial summaries of the findings confirm the initial assumptions that are the premises behind AWE.

Work that is done at home is often not done in an appropriate built environment. Nearly three-quarters of the respondents doing work at home are not performing this

\textsuperscript{12} Described in detail in section 2.2.3.1
work in a home office/study. 65% of primary computers are not in an office/study and
45% of primary computers in home environments are not at desks.

Privacy is an issue for work at home. At first glance privacy concerns are not that
great: 52.8% say “very much so” when asked if they have enough privacy. But this result
is driven in large part by the number of one-person and two-person households in our
sample. Only 30.3% of respondents in households with three members say “very much
so.” This number falls to 24.2% in households with four or more members.
Interestingly, interruptions are more likely to come from phone calls than from people
who are co-present.

Work-related storage concerns were reported by 40% of the respondents. These
concerns were primarily with the amount of storage and not the type of storage or its
location in the home.

Most of these respondents (89%) have a working computer in the home. Of those
with a working computer in the home, more than half have more than one computer,
though many of these computers are not networked. Asked to think about their primary
computers, respondents indicated that 55% of their primary computers are desktop
computers and 45% are laptops. 73% of the primary computers are used for work and
88% for recreation, 44% for school and 61% for personal business. 30% of respondents
have more than one landline, and 75% have at least one cell phone.

Respondents are doing a variety of tasks on their home computers. 60% do at
least some bill paying online; 55% do at least some banking; 42% do some credit card
accounting; 55% do some of their newspaper reading online (though 50% of these
individuals say they prefer printed newspapers to online ones). 70% of respondents reported that they gift-shop online, but in this case only 40% of these respondents would prefer to go to an actual store.

4.3.3 Task Analysis of Working Practices

A task analysis was conducted to provide a detailed look at user needs and preferences, and to help generate design requirements for AWE. The task analysis involved 1.5 hour interviews with knowledge workers in their everyday work settings. The participants interviewed were workers who gather and process large amounts of information and then compose new information products while doing their work. The participants included 4 architects, 4 teachers, and 4 accountants in order to assess workers who worked with primarily visual-spatial, verbal and numerical information. The interview data were analyzed with the goal of understanding, in fine detail, how these workers gather, organize, store, communicate and compose information, both electronic and paper-based, using their current work technologies. The results of this analysis were compared to similar but older studies of knowledge workers. A summation of the findings is provided here.

Despite the perceived trend in recent years away from paper information display and towards electronic information display, most of the workers in our study used both paper and electronic information displays at every step of their work process. The workers in this study used paper for tasks such as note taking, information storage, drawing, editing, composing and group discussion; they often printed electronic documents in order to work with them on paper; and they often categorized and laid out
important paper documents near their focus of attention. Thus, the perceived trend
towards the "paperless office" (BONDARENKO & JANSSEN 2005) was strongly
evident in the data. Our study supports and updates previous studies in this respect, and is
not unlike the phone surveys that indicate that half of those who read the newspaper
online prefer a paper format.

Electronic information processing technologies were frequently used along with
paper. In a common sequence, workers would compose a draft work product (e.g., a
drawing or a text report) in an electronic format while looking at both paper and
electronic information sources, then print the work product out and edit and annotate it by
hand, and finally enter the edits into the electronic document.

Earlier, informal work products were communicated to other workers
electronically; later, more formal work products were communicated using paper.

4.3.4 Design Guidelines Drawn From the Ethnographic Findings

Drawing from the findings of the phone and on-line surveys as well as the task
analyses, the research team developed a list of design guidelines that informed the
development of the physical AWE prototype. These follow here and are made evident in
the physical AWE prototypes:

(1) Multiple information displays are desirable in work environments and
should be located in close proximity to one another.

(2) Displays of information that is digital, printed or a mix of both should be
proximate to users for easy accessibility.
(3) Computer displays are most supportive if aligned vertically and horizontally with respect to one another.

(4) Space should be allocated for hand-written notations made by users in conjunction with activities involving printed and/or digital information.

(5) Printed information that is used frequently should be made very accessible by making ample space for it, primarily atop horizontal work-surfaces (mostly in piles or within binders), but also on vertical surfaces.

(6) Work environments should accommodate multiple people, sitting side-by-side or across from one another, and engaged in collaborative activities that may involve computing.

(7) Work environments should provide a large white board and/or computer display for group brainstorming and presentations.

(8) Work environments should provide a degree of privacy by blocking unwanted visual access and auditory intrusion.

4.4 Three Concepts for the Robot-Room of AWE

The novel aspect of AWE is its ability to continuously “morph” to accommodate a wide range of user needs by way of its smooth, continuously deformable “smart” and user-controllable surfaces. These intelligent, morphing surfaces are the critical enabling aspect of AWE. The AWE initial proposals envisioned three alternative concepts of the robot-room employing continuum robots: (1) a room comprised of bending, twisting and shape shifting ribbons; (2) a room comprised of a continuous surface of triangulated,
shape shifting panels; and (3) a room comprised of shape-shifting ribs. All three concepts share a structure of continuum robots enveloped in a malleable skin.

4.4.1 Robot-Room / Concept-1

The first concept of the robot-room accepts the conventional room where AWE is to be installed as the envelope of the Animated Work Environment. (FIGURE 4.2) shows a typical room with AWE presented as an insertion of a series of shape-shifting, ribbon-like components: a storage wall that bends to become a ceiling that finally becomes four moving arms holding computer screens, and a morphing work surface. The action of these ribbon-like surfaces, bending, twisting and shape-shifting, is presented in Figure 4.2

4.4.2 Robot-Room / Concept-2

The second concept of the robot-room is a mostly seamless, three-dimensional envelope rather than the collection of components (e.g. the moving arms for computer screens and morphing work surface of the first concept). This second concept furthers a characteristic of the first concept, where the storage wall bends to create a roof and extendable arms. This continuous surface of the first concept lends AWE the sense of
being an environment in-and-of itself, outside the limits of the conventional room. It is an environment, however, not closed but with two open ends created by its extended ribbon which folds along parallel axis (and potentially twists at the four arms carrying computer screens).

The second concept is an envelope, a closed form, with no open ends and what might be called a “blob.” A blob, as defined by architect Greg Lynn, “connotes a thing which is neither singular nor multiple but an intelligence that behaves as if it were singular and networked, but in it form can become virtually infinitely multiplied and distributed” (LYNN 1998) Lynn argues that a blob is an appropriate concept for architecture because the life of architecture envelopes is dynamic, changing and subject to innumerable influences.

An entire area of architectural research and practice has developed virtual and real “blob” architecture. Given the purported promise of a “blob” in creating a new architecture, responsive to today’s demands, it is curious that, “in the end, a form is chosen that is static – static like a sailing boat, which has a form that allows it to perform well in many different situations”. (LOOTSMA 2002)
There are numerous examples of blob architecture – Blobmeister: DigitalReal is an entire book devoted to them – that employ sophisticated 3-D NURBS software to create complex “blob” forms which are then translated into physical, static buildings. The AWE project, however, is concerned in Concept-2 with a more radical research: an opportunity, by way of continuum robots, to realize the promise of blob architecture not as a malleable complex form framed on a computer screen that then becomes static as a physical entity in the built environment, but rather as a dynamic, user-controllable, environment lifted from the confines of the computer screen and made physical – an animated architecture response to human needs. This is more the vision the radical 60’s and 70’s concepts for an open, responsive system and more recently the vision of Mitchell and Oosterhuis.

For Concept-2 of the AWE robot-room, the research team proposed to develop, effectively a hybrid of a work environment and a blob not unlike that created on-screen by Greg Lynn (FIGURE 4.5). Figure 4.6 provides a sense of this animated work environment that user’s morph to accommodate their needs and whims.

As a physical, morphing blob architecture, Concept-2, works particularly well with the behavior and characteristics of continuum robots. The morphing of AWE’s surfaces will be significantly more general than simple configuration-changing envisioned to expand beyond the use of traditional hinged or sliding joints. The AWE
The project goal is to enable controllable and fluid movements of continuous sheets (e.g. walls, task surfaces) to suit the needs and whims of the user.

Accordingly, we will adapt the emerging technology of continuum robots. Continuum robots feature continuously evolving backbones with no rigid “links” as in traditional robots and architecturally engineered structures.\(^\text{13}\) An example of a continuum robot that would provide the structure of the robot-room and enable its shape-shifting is shown in Figure 4.7. This is an extrinsically actuated continuum robot (external tendons determine the shape). This technology was adapted to the initial designs due to its strength, inherent compliance and ease of shape control.

The AWE Project proposes the use continuum robots as boundary actuators for networks of flexible surfaces which make AWE. Sensors, displays, accessories, etc., will be embedded in the surfaces connected by the continuum robot actuators. Ultimately a “patchwork” of surfaces is envisioned, as in figure 4.2. However, the initial work considers a smaller element of the more general structure, composed of several elements.

\(^{13}\) More details of the technology and its possibilities are given in (Walker 2001)
Concept-2 shares resemblance with the recent “Muscle Body” pavilion of Oosterhuis and his *Hyperbody Research Group* – a full-scale prototype of a blob architecture comprised of a continuous skin and 26 digitally controlled “muscles” manufactured by Festo, enabling it to shape-shift (FIGURE 2.10). This prototype robot-room is set-up as a “game” accommodating half a dozen or so “players” whose movements are detected by pressure and proximity sensors imbedded in the skin. As the players move about, their movements are translated into changes of pressure in the muscle-bladders which alter the form of the enclosure.

In the Muscle Body precedent, however, the functionality of the physical adaptability introduced is limited. The adaptability of the architecture is restricted to producing compelling visual (but not functional) effects, and the movements are not predictably controllable and/or programmable (OOSTERHUIS 2005). These limitations are overcome in Concept-2, where the more nimble, controllable continuum robot is employed to create an animated architecture responsive to the particular needs and whims of human beings engaged in the particularly intensive practices of working life. The AWE team also envisioned that some parts of the blob may be fixed rather than shape shifting, adding another level of complexity to our efforts. The AWE full-scale working prototype that follows from the three three-year funding cycle of this investigation embodies a range of “off-the-shelf” Information Technology components that, when suitably exploited, facilitate working life in an increasingly digital society.
4.4.3 Robot-Room / Concept-3

In our research, Concept-3 of the robot-room is simply an extension of the blob investigation of Concept-2 but substitutes a series of shape-shifting O-rings for the triangulated panels. The sense of Concept-3 as a series of shape-shifting ribs is shown in the digital model from the architectural office of Jacob and McFarlane in its design of the (static) café realized within the Pompidou Center (FIGURE 4.8). Again, the AWE team reinterprets this static form as shape shifting for Concept-3.

![Figure 4.8: Concept-3 as a series of ribs after Jacob MacFarlane (AWE Team)](image)

4.4.4 Towards A Total Concept Of Awe

The AWE team aimed to present virtual and physical models for all three robot-room concepts, and provided comparative evaluation of these. It is important to remember, however, that these formal efforts, principally of the architect and robotics engineer, to develop a programmable, physical robot-room environment will, were adjusted in response to the findings of the social scientists drawn from their surveys and usability studies.
The total concept of AWE was envisioned as a complex application that promises to: (1) integrate IT seamlessly into working life and leisure, home and office; (2) manage the “multi-tasking” demands of individual and groups of workers by facilitating and remembering varied projects requiring different configurations of digital and analog devices and information; (3) allow work environments to adjust for differences in physical and cognitive abilities across users, diminishing the barriers caused by disabilities, age and ageing, and enticing elders and those with special needs to participate in working life; and (4) promote a meaningful sense of connectedness to the place of work, to new technologies and to communities of working people – local and global.

4.5 Awe’s Prototype-1 And Three Scenarios

The research team constructed an early, full-scale, working prototype. Envisioned as more a “sketch” than something final, this early prototype served several objectives: (1) to demonstrate for the first time the concept of a continuum robot as a panel rather than a trunk; (2) to realize the total “atmosphere” of this intelligent environment – its qualities and potentials as a place for human activity; and (3) to allow this transdisciplinary research team an early opportunity to work in concert to conceive a total working prototype. Three scenarios involving working tasks and employing the prototype were videotaped to show the potential applications of AWE.
4.5.1 Scenario-1: AWE at the Office / Protecting Privacy

Jennifer, an Oncologist, is analyzing private documents pertaining to a particular patient’s case using AWE, which is installed in her medical office. Jennifer has set the various documents to appear across two of AWE’s three programmable “ribbons” (FIGURE 4.9a). AWE has adjusted its lighting to support the task. Jennifer’s Office Manager, Rachael, unexpectedly enters Jennifer’s office to ask a question about patient billing (Figure 4.9b). Jennifer positions her hand near AWE’s proximity sensor on one of the two ribbons showing private documents. Moving her hand to the left moves that ribbon into a configuration that shields the patient’s private documents from her co-worker (FIGURE 4.9c and 4.9d). After answering Rachael’s question, Jennifer announces that she’ll need to leave the office for home in one hour to tend to her ill dog, Zam. She asks Rachael to make sure the patient’s test results are forwarded to her at home as soon as they arrive at the office. Rachel agrees to do so, and reminds Jennifer that she’ll be dropping by her house in the early evening to discuss their upcoming vacation plans. After Rachael leaves, Jennifer returns AWE to the configuration set before Rachael entered her office (FIGURE 4.9e), and continues her analysis of the patient’s private documents.
FIGURE 4.9. Scenario-1: (a) The doctor uses AWE to analyze patient documents; (b) The office manager arrives; (c) The doctor motions her hand before AWE’s ribbon display to maneuver it away; (d) The patient’s privacy is protected from view; (e) The office manager departs; the doctor returns AWE to its earlier configuration and continues her analysis. (AWE team)

4.5.2 Scenario-2: AWE at Home / Waiting for Test Results

Jennifer is home watching the movie “Pirates of the Caribbean” displayed on one of AWE’s three ribbons and played over AWE’s integral audio component (FIGURE 4.10 a). Jennifer meanwhile awaits the follow-up test results for the urgent patient case she was analyzing earlier today in her medical office. A text message scrolls across the bottom of the ribbon displaying the movie: “Urgent Test Results.” Jennifer selects “Patient Data Mode” from a number of pre-configured modes displayed on another of AWE’s three ribbons. AWE responds to the command, arranging itself into a configuration well-suited for this task (FIGURE 4.10b). While the movie continues to be displayed on one of AWE’s three ribbons, the incoming information appears across the other two ribbons in multiple displays of patient data in text and images.

AWE has adjusted itself to the dual function of playing home entertainment and receiving incoming data. Nevertheless, Jennifer wishes to “fine-tune” AWE’s ribbons to display the patient documents according to her preferences. To do this, Jennifer moves her hand above the ribbon’s proximity sensor (Figure 4.10 c – the circular insert) and motions her hand reposition the screen slightly, according to her assessment of her particular needs (FIGURE 4.10 d). Jennifer examines the records, sends an email with her assessment of them, and returns to watching her movie.
FIGURE 4.10. Scenario-2: AWE at Home / Waiting for Test Results: (a) the doctor, at home, watching a movie presented on AWE. AWE adjusts its lighting and sound accordingly; (b) AWE re-configures as a patient’s test results arrive from the office; (c, insert) the doctor “fine-tunes” one of AWE’s smart ribbons with her hand via proximity sensing; and (d) AWE is now configured to her liking. (AWE team)

4.5.3 Scenario-3: AWE at Home / Computing Collaboratively

It’s early evening at Jennifer’s home. Jennifer is paying her bills – printed and digital documents – using AWE (FIGURE 4.10a). Rachael arrives with numerous travel brochures for Jennifer to consider in planning their vacation together. Rachael found a special offer on a tour of Spain; the offer is only valid until midnight. AWE allows Jennifer to “cover” her printed bills with a second work surface (Figure 4.10b) so that she and Rachel can switch to vacation planning without disturbing the thoughtfully-arranged stacks of papers. AWE allows Jennifer to move between virtual and physical desktops to accommodate this new task, while not losing her already completed work or her train of thought.

Rachel and Jennifer begin working together on their vacation planning. They look through several brochures. Rachel points to one that she is particularly excited about – the “special offer.” Jennifer uses her smart phone to click on the barcode printed on the
brochure. This action brings up the Tour’s webpage on Jennifer’s phone, which she then projects on AWE’s ribbon display (FIGURE 4.11c). Jennifer then clicks on the image of Toledo from the on-line brochure, which links to details concerning the touring of that Spanish city. Rachel and Jennifer use the web to interactively explore various aspects of the Spanish Tour outlined in the printed brochure and associated webpage.

FIGURE 4.11. Scenario-3: AWE at Home / Computing Collaboratively: (a) the doctor, at home, employing AWE to work on printed and on-line bills; (b) the office manager – also a personal friend of the doctor – visits to help plan their Spanish vacation. AWE’s “second surface” maintains the organization of the printed bills; and (c) the doctor users her smart phone to display information drawn from a printed barcode on a travel brochure to AWE’s smart-ribbons. (AWE team)

4.5.4 Prototype-1 Discussion

The three scenarios described above demonstrate the potential of AWE to protect private digital documents from view; to organize the inter-relationship between home and office work; to handle complex groupings of digital and printed documents; and to work collaboratively within a computing environment.

However, this work was still an early phase of the research. The “smart ribbons” lacked the envisioned suite of touch and/or proximity sensors. They are also currently
formed from a single continuum robot actuator (FIGURE 4.12) at the core of a foam ribbon, which restricted the movements available. In our ongoing work, the “smart ribbons” were redesigned to feature multiple actuators providing the user with more options for their placement and use. The panel of multiple actuators will also represent a first for continuum robots.

The early full-scale prototype room is also lacking the “filing system” for integrating printed documents (via RFID tags) and digital document originally envisioned and shown on the back wall of the digital visualization (FIGURE 4.11a). The next iteration of AWE proposed a higher connection between paper and digital documents to respond to this absence by the addition of “file boxes,” each dedicated to a particular project as assigned by the user, each having space for printed documents, an RFID reader to organize them, and a small computer screen which lists digital documents assigned to it and offering, on-screen, views of their first pages.

Note that the three scenarios considered here present certain information technologies, integral to AWE, which lie outside robotic and architectural design; these
technologies are either commercially available or suited for development by other researchers in the IT research and industrial community. A key goal of the AWE project is to integrate existing and emerging technologies, and hopefully to stimulate new research in related IT and human interfaces.

The next phase envisioned a more economically-scaled AWE employing a single more complex ribbon oriented in the vertical direction that accomplishes much of the functionality of the three ribbons of the early prototype presented here.

4.6 Awe’s Prototype-2

Prototype-1 represents an early stage of the research; Prototype-2 (FIGURE 4.13) retains and even extends the functionality of the initial prototype in a more compact mobile workstation. It integrates the work surface and the programmable ribbons into one continuous physical construction – a more economical solution, on multiple levels. Its features a “filing system” for integrating printed documents (via RFID tags) and digital document which allows bibliographical information for each document in the box is entered into AWE by the user, displayed on the box’s screen, and entered into the associated digital document.
The ribbons of Prototype-2, unlike those of Prototype-1, can display information on two faces to accommodate two users facing one another (FIGURE 4.15 left); can be moved across the work surface to effectively “enlarge” the physical work surface for special tasks (FIGURE 4.15, center), and retract altogether to open the work surface for tasks not involving computer screens (e.g. meetings, physical model building, manual aspects of graphic and package design) (FIGURE 4.15, right).

Finally, the workstation of Prototype-2, unlike that of Prototype-1, affords collaborative computing on a larger scale by allowing it to connect to a series of like
workstations along a programmable spline. In the configuration shown (FIGURE 4.16), the programmed configuration of five AWE workstations along a spline allow for – at once – intimate collaboration, individual work, creative projects requiring a full work surface, and a conference table for meetings. One could imagine the workers of a small office, or a group of individuals within a larger office structure, “tuning” a series of joined AWE workstations to meet the requirements of different office projects. We see this last aspect of Prototype-2 as a tremendous leap beyond the typical office network of desktop computers sitting atop office desks of like design, organized in repetitive rows.

FIGURE 4.16 AWE affords collaborative computing along a programmable spline. In the configuration shown, the two seats at (a) allow for intimate collaboration, while the facing seats at (d) facilitate individual work. The seat at (b) allows for creative projects requiring a full work surface. The four seats at (c) allow for meeting. (AWE Team)

Prototype-2 was a fast iteration and remained as digital format. It only explored one working surface and did not explore different environmental qualities for working life; the next iteration, Prototype-3, was an evolution of both design in a more exploratory environmental research which embedded more complex levels of robotics and working interactions.
4.7 AWE’s Prototype-3

In-concept, this new prototype of AWE employs two key components: a vertical “spine” of eight stacked panels framed in aluminum, each five-feet wide and linked together by eight motors (FIGURE 4.13 AND 4.14); and a horizontal work surface on wheels, of roughly a boomerang shape. On the vertical spine, mounted on the lowest frame, are two large computer displays and a white board oriented in a concave, “wrap-around” configuration most satisfying to users of multiple displays. The next-lowest panel has capacity for one or more such displays.14

FIGURE 4.17 A translation of “invertebrate-like” continuum robot technology in the AWE project as considered in this paper: left, a trunk-like form previously developed and extensively tested by the investigators; center, a planar surface as initially conceived for AWE; and right, a hybrid of these two at a different scale in the current AWE conception. (AWE Team)

14 At this time the design guiding AWE was the concept of an entirely malleable, folded, space working as a chassis accommodating a different range of digital and analog tools. The vertical wall concept came naturally as an evolution of a continuum robot into a bigger, longer, habitable scale. Discussions with the group led to believe that it wouldn’t be possible to use Festo muscle to create such malleable space. The most important decision related to the concept of a robotic foldable wall was made in this point, this was: Instead of using continuum links, rigid links with motors as connections were used. This decision made the movement of the wall possible, however, an multidirectional part of its movement was sacrificed, rigid link with motors is one directional.
The six panels above these two lowest panels – all six having the same dimensions – designed to contain smaller computer displays, tablets, magnetic whiteboards, audio and lighting, sensors, a large-format projection screen, and a range of digital peripherals and analog accessories or “tools”. It was envisioned that such digital and analog tools will be mounted to metal panels sized to match the dimensions of each of the six identical frames, and that the panelized tools are interchangeable. This construction affords the users the ability to plug-and-play the individual panelized tools into any of the six uppermost frames, as working tasks and leisure activities demand.

FIGURE 4.18 Early render of the new AWE prototype-3. Eight aluminum frames and eight motors create the programmable “spine” of AWE. Larger computer displays occupy the lowest two frames; interchangeable panelized “tools” are “plug-and-played” into the upper six frames. (Author)

The advantage of the new prototype is that its programmable spine can be organized in several standard modes to create spatial configurations much more supportive of working and playing in a hybrid, digital-analog collaborative work environment. Standard spatial configurations are selected by the user from a touch screen mounted on the horizontal work surface, and include COMPOSING, PRESENTING, and
GAMING (FIGURE 4.19). Once AWE assumes the selected spatial configuration, the user(s) can then “fine-tune” this configuration to individual specifications by gesturing AWE’s proximity sensors and saving the modified configuration under a new name (e.g. “COMPOSING – Laura and Steve”). As well, the horizontal work surface – on wheels and structurally independent from the vertical spine assembly – can be repositioned and rotated to create a physical environment more suited to, say, CONFERENCING.

![FIGURES 4.19 Early renderings of AWE set in COMPOSING, GAMING and CONFERENCING configurations. (Author)](image)

4.7.1 Iterative Multidisciplinary Design Cycle for Prototype-3

Prototype-3 envisioned a more economically-scaled AWE employing a single more complex ribbon oriented in the vertical direction. This prototype accomplishes much of the functionality of the three ribbons of prototype-1, enhances the connection between paper and digital documents, and further integrates existing and emerging IT technologies. This section presents an overview of the three-year design evolution of prototype-3; its iterative phase brings together the historical and theoretical study of work.
environments, the data extracted from the ethnographic research and surveys, an understanding of continuum robots, and a developing a sense of design to the workplace.

Initial sketches of prototype-3 (FIGURE 4.20) demonstrate how a continuum robot concept can become an environmental architectural experience. A folding ‘wall’ contains two different vertical folding surfaces – one with 16 panels, the other with 13 panels – affording diverse single and group working configurations.

FIGURE 4.20: First iteration of Prototype-3. (Author)

The initial design phase of prototype-3 considered different interpretations from the surveys and ethnographic findings. (FIGURE 4.21) This phase consisted of an intense graphic description of different work interactions, developing different design affordances and scenarios. The process is designing for interaction instead of forcing

15 Designing functional spatial works lead me to hypothesize the design of two vertical malleable elements affording real-time responsiveness, capable of adapting to multiple work configurations. As seen in FIGURE 4.20 (Right) two vertical foldable elements seem – after the design and construction of prototype-1 and the design of prototype2- like the proper solution to explore the use of continuum robots into a small-scale workstation. These initial sketches became the base for AWE’s functional and aesthetic design search. The high number of panels at this time suggested multiple possibilities. Due to multiple technical issues the two side folded surface was simplified to just one.
users to adapt to a given design. Prototype-3 is now a very thin surface responsive in both vertical and horizontal dimensions.

The initial design phase focused on accommodating diverse group activities. This demanded a holistic understanding of new patterns for working life. Prototype-3 is composed of multiple different panels embedded by computer screens and lights accessed on both sides by different users. (FIGURE 4.22) 16

16 This phase considered the vertical surface affording work configurations for both sides. The opportunity of having a multi-folded animated wall seemed to precious to be only used in just one. Such design decision replaces the previous two wall hypotheses (FIGURE 4.20). Design studies suggested instead one wall being used in both sides, a certain resamblence to Prototype-2, the affordances of multipe collaborating configurations played a major role in deciding where each panel would go and what angle would it be.
FIGURE 4.22: AWE is composed of multiple different panels embedded by computer screens and lights accessed on both sides by different users. (Author)

AWE begins to acquire certain physical properties. This design phase expanded the addition of different side vertical rails to provide structural stability. (FIGURE 4.23) Ethnographic research, surveys and collaborative design activities led to reducing the number of panels and yielded some playful ‘wall’ configurations.

FIGURE 4.23 AWE acquires certain physical properties; and starts to accommodate different environmental qualities. (Author)

The next phase established the prototype’s spatial dimensions and physical qualities. The workstation length is 1.5 meters (about 5 feet), a standard size calculated to accommodate two people composing or collaborating side to side. (FIGURE 4.24) Also established was the number of panels: eight; two of these panels accommodate computer displays and six of them accommodate different peripherals. Another important issue was the layout of the different displays: Where should they be, and how many displays can one person use effectively.  

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17 The decision to set the design with eight panels was based on technical cancers. At the times the group discussions led to a consensus that eight seemed the appropriate number to shape an animated work environment and explore novel robotic movements, more than that was considered redundant at this time.
FIGURE 4.24: Here it was decided both prototype dimensions, 1.5 meters, and some of its material qualities (Author)

For the first time in the AWE project the motors are shown to a scale in the drawing. Unexpectedly, The motors to support the wall movements are bigger and heavier than initially predicted. The thin strip first envisioned loses part of its elegance (FIGURE 4.25 A) and gains two bulky vertical rails. To support the motors, the panel design was altered: instead of rectangular, they become a flat ‘H’ shape to fit the motors with a 9 centimeters (approximately 3 inches) spread apart. (FIGURE 4.25 B) ¹⁸

Moreover two concerns, lab size and budget, played a major importance in the design decisions. The exploratory nature of this research expected the use of a lot of technological features. The working prototype needed to address such issues.

¹⁸ – The arrival of the motors to the lab had a major impact in the workstation design. First, it led to the design of movement as a central spine where with one panel per motor. To adapt to such motion the panels were redesigned into the ‘H’ shape with two horizontal and four vertical profiles. Such tectonics - height and brackets and connections guided AWE’s skeleton form and final aesthetics. All pieces were designed to fit the connection between motors. A latter interaction would add different hinges and brackets to the panel adding more complexity to the wall.
At the same time as the design of the wall was evolving, the concept of an Animated Work Environment was moving from a movable wall to become a complete interactive environment. To accomplish these different propositions, different horizontal work surfaces were presented. Figure 4.26 shows early designs for interactive work surfaces. Initially, this part of the design was conceived as static furniture embedded with different peripherals and electronics, and housing an array of smaller drawers. This concept was later discarded due to its inability to adapt to highly mobile, multi-configuration work patterns.
The concept of the ‘smart box’ previously explored in Prototype-2 is designed to fit the wall as a way to accommodate both printed and digital materials. (FIGURE 4.27) This concept is later discarded as IT responses were judged to better satisfy these needs than the physical responses to problems of storage. Another step was the introduction of a ‘boomerang’ multi-configuration shaped desk accommodating different working configurations.

A second iteration on the boomerang table shape; it can accommodate two people in a collaborative composing mode, left, and a small two people meeting and at the right a four people meeting. (FIGURE 4.28) ¹⁹

¹⁹ Once the design of the wall was set by its tectonic elements, the design concern deviated from the vertical to the horizontal work surfaces. This design phase was characterized with a redesign of the
In this phase the team started to assemble the prototype base. Two main factors guided its design. First the base dimensions were dictated by the amount of equipment necessary to move the wall (e.g. computers, amplifiers and control boxes) and the wall’s weight and movement. (FIGURE 4.29) Second the base’s dimensions were calculated according to structural needs, providing counterweight of approximately one ton. For this, blocks of pre-cast concrete were used. More details about the base design are in the section 4.8.7.

Based on the data on contemporary work patterns, it seemed appropriate to embed different sets of peripherals and electronics into everyday use work furniture. What better way to improve work conditions than to ‘pump’ the work desk with electronics. Such hypotheses was later refused as both ethnographic studies and surveys suggested that what was needed is not so much a powerful single work-surface, instead one which could accommodate multiple single and group work configurations.
Prototype-3 also started to acquire different elements such as the privacy screen located at the top of the last panel which afforded more concrete environmental conditions such as the cocoon oval shape. (FIGURE 4.30) The end of the wall could accommodate a laptop so that two people could interact in gaming/collaboration mode. 20

20 Once the panel design was set, an intense design phase consisted in finding affordances for the panels shape and the skeleton as a chassis. The eight panels folded and moved to acquire work possibilities. This led to the design of AWE’s six work configurations. Moreover the chassis became a plug-in-play of diverse digital and analog elements. Considered for the plug-n-play were different sets of digital displays, lights, sensors, and a privacy screen.
Figure 4.31 shows the frame covered with what was initially envisioned as white *allucobond*, a material that allowed it to become an entire drawing and magnetic board. *Allucobond* was discarded due to its weight. With consideration, most future developments of the prototype were studied directly in the physical demonstration and not as a virtual simulation.

![Image of AWE envisioned with its frames covered by Allucobond](image)

**FIGURE 4.31** AWE envisioned with its frames covered by *Allucobond*. Lights were embedded in the middle section of each panel. (Author)

With attention focused on the built prototype team researchers meetings revolved around the horizontal working surfaces. A great number of different propositions (FIGURE 4.32) were prototyped in cardboard at 1:50, 1:20 and full-scale to be analyzed and compared by all members of the team.  

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21 The design strategy for the horizontal work surface was based on the concept of ‘design for iteration’. (MOGGRIDGE 2007) a functional concept which concerns not so much with the design of objects per se, but the affordances which it requires. In the of AWE’s horizontal work surfaces, AWE design became the result of a geometry of curved shapes extracted from two possibilities of working interactions and collaborations. (1) Each curve fillet afforded different collaboration configurations between two, three and four people sitting side by side; and (2) the possibility to program the work surfaces to become single, group of conference space. (FIGURE 4.34)
FIGURE 4.32 A sequence of different cardboard models of the horizontal work surfaces: Left, at 1:50 and 1:20; Right, at full-scale (Author)

The initial AWE panels were covered in cardboard to simulate both environmental conditions and work affordances. (FIGURE 4.33) Following findings in ethnographic research and due to excess of weight in the structure beyond the capacity of the motors, the middle computer display was replaced by a drawing board.

FIGURE 4.33: Pictures of AWE prototype showing five active panels three computer displays and first built set of tables. (Author)

With the robotic backbone, AWE’s configurations are more responsive possible due to the “programming” of the three horizontal mobile work-surfaces, which collectively afforded various working and leisure activities. By rotating and combing
these three “programmable” units, different modes for work are made possible: a U-shaped composing mode; (FIGURE 4.34 left) an intimate meeting mode; (FIGURE 4.34 center); and a formal conferencing mode (FIGURE 4.34 right). The three units together provide ample horizontal surface area for teamwork as well as the handling and organization of paper documents and three-dimensional physical models of various sizes.

FIGURE 4.34 Configurations of AWE’s three programmable work surfaces; U-Shape, left, intimate meeting mode, center; conferencing, right. (Author)

In the Final AWE prototype, the six aluminum panels are covered with a custom fabricated blue-and-green writable plastic. (FIGURE 4.35) The first row contains two computer displays and one drawing board. The second row one movable display, a magnetic and drawing board. All other panels contain different peripherals such as lights, cameras and proximity sensors to afford real time interaction. The new tables afford
highly nomadic work patterns and different work configurations to be set. (FIGURE 4.36)  

22 AWE’s aesthetics started as a fine elegant foldable strip, and became a rigid link panel connection. Designing for interactions in a digital society presented an overload of robotic complexities; its final form was result of technical functionalities, mechanical connections and fewer aesthetic choices. Despite that, the design was very successful in experimenting with robotic sensor programming and kinetics.

FIGURE 4.35 Diagram of Final AWE prototype with all its components. (Author)

Taken together, AWE’s three work-surfaces, its white and pin-up boards, and its computer displays promise users the ability to effectively combine tasks involving printed and electronic information – work activities most prevalent among subjects of our human-centered investigations.
FIGURE 4.36 Complete AWE as it is: six covered panels, three computers screens and three work surfaces that can be rearranged for different configurations. (Author)

4.7.2 AWE’s Six Configurations

Upon first approach, the mobile robot workstation introduced appears to be nothing more than a flat wall (FIGURE 4.37). When the user takes control it transforms into a personalized, intimate space for the focused composing of documents; or, alternatively, a configuration designed for presenting to an audience. The workstation efficiently utilizes space by dramatically transforming itself to match the needs and wants of different users. Computing, digital projection and lighting will emanate from within the workstation itself.

The design concept is not limited to the office. The workstation can function inside distinct rooms of different sizes and purposes because it can adapt its physical form. At home, for instance, the workstation supports home-office tasks; but when these tasks are accomplished, the system can provide configurations more suited to online gaming, shopping, viewing, tutoring, and creative and investigative activities.
We have designed six standard physical configurations in support of individual and collaborative human activities afforded by AWE, including those defined more by work (e.g. composing and presenting) to those defined more by leisure (e.g. gaming and viewing). These configurations were very much informed by the findings of the surveys and task analyses. The user selects a particular configuration by selecting one of six numbered buttons located just below the first frame from the base. Fine adjustments by the user will be made possible by touch sensor, gaming interface, or some other interface yet to be determined. Such user adjustments can be saved and later recalled.

4.7.2.1 Configuration-1

Configuration-1 affords intensive composing and viewing of electronic and printed information by either one user or two users working individually or collaboratively (Figure 4.38). The focus in configuration-1 is on the three lowest screens which can be positioned so that either: (1.) one or two users can focus on the same set of
displays, with all three screens positioned closest to center; or (2.) two users can work separately side-by-side with the two lower screens set apart, as shown in the figure.

![AWE Configuration-1](image)

**FIGURE 4.38 AWE Configuration-1, accommodating two users collaborating, composing and/or viewing.**

4.7.2.2 **Configuration-2**

Configuration-2 affords intensive computing by a single user who might elect to position the two lower screens towards the vertical-center as shown in figure 4.39. A privacy screen can be pulled towards the floor to block visual access from behind the user. As well, the leaf in the foreground of the figure can be folded upwards to provide partial visual access from the side, presuming that AWE is set with its other side near a wall, as shown in the figure. Should AWE be placed in a room where the wall is to the right of the user, the two outer work-surfaces, both on casters, are easily repositioned to offer the same measures of privacy.
4.7.2.3 Configuration-3

Configuration-3 affords composing by two individuals engaging in activities that don’t require that they share the same intimate space. This might be the case where the two users are working alone on different pursuits or different aspects of the same pursuit and welcome the modest distance this spatial relationship creates between them.

(FIGURE 4.40)
4.7.2.4 Configuration-4

Configuration-4 affords two users to work in the same intimate space, but back-to-back (FIGURE 4.41). This configuration suits two people gaming. It is also suited to working collaboratively; but unlike the side-by-side collaboration of Configuration-1, this configuration better supports a scenario in which the collaborating individuals are working on different but related documents (say, pertaining to a single project), or are working on different aspects of a single document.

![Configuration-4](image)

FIGURE 4.41 AWE Configuration-4, accommodating two users in a lounging, playing and/or presenting mode. (Author)

4.7.2.5 Configuration-5

Configuration-5 affords, most particularly, formal presentations requiring a projection screen. The work-surfaces of AWE are repositioned and rotated 180 degrees to allow room for the presenter, a podium, and a pedestal supporting physical artifacts as part of the presentation (FIGURE 4.42). Lighting integral to AWE’s panels is programmed to focus light onto the physical objects displayed.
4.7.2.6 Configuration-6

Configuration-6 affords leisurely viewing of videos or slide shows presented on the projection screen (FIGURE 4.43). This configuration suits the playback of movies, satellite television and other longer time-based media.
4.8 Workstation Design/Realization

4.8.1 AWE’s Computer Displays and Supporting CPU’s

The understanding of current information-processing practices and technologies gained from the surveys and task analysis guided the design of the current AWE prototype, particularly with respect to: (1) defining the computing environment (i.e. AWE’s computer displays and CPUs; see figure 3), and (2) the physical configurations the robotic backbone assumes. The latter was informed, as well, by current ergonomics standards for the spatial layout of workstations drawn from the Human Factors and Ergonomics Society. AWE was designed to be used by a high percentile of the population as it affords configurations raging from a large man to small woman.

(FIGURE 4.44)

![Figure 4.44 Ergonomic studies from AWE: Affording use by different size populations; from large man to small woman. (Author)](image)

As AWE permits up to three users computing at once, working individually or in collaboration, we have allocated three displays total for AWE. All of the displays are
user-adjustable and are mounted following established ergonomic specifications. As shown in figure 4.44 and in subsequent figures, (FIGURE 4.45), three of the screens are 19” diagonal flat-panel screens mounted on the two frames lowest to the base of the AWE backbone. Subjects in the task analysis also expressed a preference for aligning multiple displays vertically and horizontally. To accommodate this preference, the mounting hardware designed for AWE allows the two screens in the frame closest to AWE’s base to slide horizontally. If these two screens are slid apart, they better accommodate two users working side-by-side; if they are slid together so their sides abut, a single user can use these two screens. The mounting hardware for the screen just above these two sliding screens allows this screen to be aligned over the left-most screen below it. All the screens are mounted with a ball joint to allow them to be angled to achieve a “wrap-around” configuration to best suit the user(s).

![FIGURE 4.45 AWE’s three 19” adjustable screens and base.](image1)

![FIGURE 4.46 User demonstrating the horizontal movement of the screens. (Author)](image2)

Taken together, the work-surfaces described earlier, the white board and computer array described here promise users of AWE the ability to effectively combine tasks
involving printed and electronic information – the work activities most prevalent among subjects of our ethnographic investigations. The various elements of AWE assume in supporting work and play activities is described in the following sections.

4.8.2 AWE’s Robotic and Structural Backbone

The concept of robot systems based on serial arrangement of rigid elements is not new. Traditional rigid-link manipulators have been successfully deployed in numerous applications, and are well understood by the robotics community (SPONG et al 2006). What noticeably differentiates the AWE workstation from traditional robot structures is that its profile is two-dimensional (i.e. a reconfigurable surface) instead of one-dimensional (i.e. a “backbone drawn in space”). Additionally, unlike conventional robots, the AWE workstation features redundant degrees of freedom. This kinematic redundancy allows the robot to retain the position of a panel while changing the configuration of the rest of the robot (SICILIANO 1990). This is critical, for example, when the user desires to maintain a display or lighting orientation while reconfiguring the system.

Kinematic redundancy has been an important research area in robotics in the last few years. There are numerous examples of redundant robot manipulator arms in the literature (NENCHEV 1989 and SICILIANO 1990). Snake-like robots (HIROSE 1993) also feature significant redundancy. Some of the algorithms for motion planning of redundant systems developed in the literature will be applicable to the kinematically redundant AWE workstation. However, the AWE workstation is novel with respect to the state of the art due to its surface-like nature, and the nature of its environment. Unlike
redundant manipulators, the entire body – not only the end effector – is important in the user task. Unlike typical snake-like applications, the vertical plane is a key factor in design considerations, given gravity’s impact on the system.

AWE’s robotic system consists, for the most part, of eight five-foot-wide aluminum frames of between one and two feet in height, linked by eight motors. The eight aluminum frames of AWE serve as the structure for sheathing which transforms the frames into panels.

To effectively alter the configuration of this system, designed for the worst-case but improbable scenario of having all eight frames cantilevered into an outstretched, horizontal configuration, the five motors closest to the floor are coupled with harmonic drives. To ensure the panels move fluidly together, through the various configurations, hinges near to the two extremes of every frame were placed. This allows the system of frames to move much like a typical linked, metal watchband, but at the scale of a room.

4.8.3 Overall Multi-Panel Design

The initial prototype is a multi-panel structure, folding within a plane. Initial analysis suggested that eight panels and eight degrees of freedom would be sufficient to provide the variety of configurations desired for testing. After the detailed dimensions were defined, the design was simulated in the modeling program, SolidWorks (FIGURE 4.47). Aluminum was chosen as the material for panel construction, due to its lightweight. Based on the weight of aluminum, calculations were made to determine the weights of each of the panels and the system overall. (FIGURE 4.48)
4.8.4 Actuator/Transmission Selection

Conventional electric motors were chosen for the workstation’s actuators, with actuators being located adjacent to each panel. This was due in part to the resulting simplicity and modularity of design, compared with alternative remotely actuated tendon-based designs.

Specific motors were selected for each panel. One of the key criteria in this choice was the extreme torque requirements required to move the panels. These torques were
calculated at the worst-case load scenario, where the entire workstation was configured horizontal to the ground, making the center-of-gravity as far as possible from each respective motor (FIGURE 4.49).

Figure 4.49: Depiction of large torque-inducing orientation of the second lowest motor

The largest torque constraints, upwards of 2200 Nm, are on the base, bottom-most, motor. At this scale, the only traditional motors available that could achieve this were overly large—two to three feet in diameter. Instead, our design employs harmonic drives, greatly increasing the amount of torque that can be supplied in a smaller motor.

Of the eight motors within the design, five have harmonic drives attached to them. A faceplate is attached to the motor’s gearbox which itself is attached to the drive with a collar around the shaft extending from the gearbox. The last three motors, most distal from the base, are attached directly by the shaft on the gearboxes. The harmonic drives, while enabling sufficient torque; correspondingly restrict the speed at which the panels can travel. This is not considered a disadvantage for the workstation application, as slower movements match well with the proposed application, and is actually preferable from both safety and control perspectives.
4.8.5 Actuator Integration

After selecting the motor/drive combinations, the attachment of the motors were integrated into the panel design. Room was left to fit the motors into the panels so that the gaps between the panels were minimized while retaining the maximum flexibility of movement. The brackets designed to attach the motors to the panels can be seen as blue plates in Figure 4.50. These plates were also created from 6061 T6 aluminum in order to make the wall system light while retaining as much strength as possible. The torque calculations were performed incorporating the weight of these plates, the additional weight of the motors, four flat panel computer screens, and an additional 10 pounds (4.5 kg) in each panel to accommodate future sensors and peripherals.

4.8.6 Torsion Management

Responding to the potential for the panels to twist around the vertical axis, brackets were created to connect the panels along the sides (FIGURE 4.50). These would limit the torque along the z-axis the panels could exert, as well as give more stability to the system. These brackets will be connected through a simple hinge joint.

Figure 4.50: Hinge and smaller bracket design
4.8.7 Base Design and Construction

With significant mass being moved within the workstation structure, a solid foundation for the system is essential. After significant design iteration, a concrete base was selected. The final base design responded to the weight restrictions of the building structure supporting the workstation, the ergonomics of having someone sit at a desk in front of the AWE workstation, and the space requirements needed for hardware.

Three reinforced concrete slabs were chosen for the base of this system. Each slab had to have dimensions and material properties to support the weight of the robot without compromising the lab floor resistance; the blocks that were ultimately selected give 100 lbs-per-square-foot pressure to the floor. A workstation base (containing all the control electronics) was designed and constructed from Bosch aluminum components. To attach the base to the concrete, holes were drilled in the concrete slabs and screw sleeves were secured in these holes with epoxy. Bolts securing the Bosch aluminum tubing system were threaded into the screw sleeves, securing the framing to the slabs.

To determine the total mass of the concrete base, simple calculations using torque and the center-of-mass were used. The worst-case scenario is shown below in Figure 4.51. The biggest concern was to make sure the torque created at the center-of-gravity of the concrete base significantly overcame the torque created by the wall when it was positioned in a horizontal fashion.
4.8.7.1 Base Construction And Testing

The base (FIGURE 4.52) was put in using forklifts because each block weighs around three hundred kilos. A structure frame made from *Bosh* metal connectors was constructed over it.

From the concrete base the motors and panels were assembled. Shown in Figures 4.53 and 4.54 is an early assembled version of the wall with five motors. Motors are
numbered from 0 through 7 from the concrete base up. Each motor moves the panel above it to change the configuration.

Figures 4.53: Front view of AWE flat (Author)

Figures 4.54 shows initial stages of the workstation construction in a composing configuration. At this stage, the experiments were successful, the panels move easily.

Figures 4.54: Composing configuration for AWE (Author)

The gains for each motor needed to be set. Table 1 shows the maximum speeds that the motors assemblies allow. The motor assemblies 0 through 4 and 7 are all use the
same motor. The different max voltage to each motor is differs because the input torque allowed by the harmonic drive attached to the motors.

<table>
<thead>
<tr>
<th>Motor assembly number</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max voltage to motor (V)</td>
<td>3.87</td>
<td>6.11</td>
<td>6.11</td>
<td>7.13</td>
</tr>
<tr>
<td>Max output speed (rpm)</td>
<td>1900</td>
<td>3000</td>
<td>3000</td>
<td>3500</td>
</tr>
<tr>
<td>Motor assembly number</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Max voltage to motor (V)</td>
<td>7.14</td>
<td>36</td>
<td>24</td>
<td>15</td>
</tr>
<tr>
<td>Max output speed (rpm)</td>
<td>3500</td>
<td>2650</td>
<td>8380</td>
<td>6270</td>
</tr>
</tbody>
</table>

TABLE 1: Voltages and speeds for each motor

4.8.8 Workstation Control

Control of the overall system is achieved via independent controllers for each panel, within a custom real-time control environment. Panel angle feedback is obtained from encoders on each of the motors. The control computations are performed in real time using a Pentium PC, with I/O achieved via a commercial ServoToGo interface board. The input signals are amplified by commercial Techron amplifiers. The overall control structure is shown in Figure 4.55.
A standard PID controller is used for each panel. The position, integral, and derivative gains were tuned for each motor. For the case of the motors with harmonic drives, voltage limit was established and the proportional gain of the controller is set to a large number to ensure that only near the tail end of the movement will the voltage, and therefore speed, taper off. With the relatively slow speeds, tuning of the controller for each of these panels was relatively straightforward and transients are not a major issue.

The controllers are implemented on a PC with an Intel Pentium 4 Processor, operating at 2.86Hz, running QNX 3.2.1 real-time operating system. In this environment, QMotor 3.22 allows the user to achieve real-time control response. The control algorithm was written in C++. (APPENDIX C) The system is currently operated in set point mode moving between fixed pre-set configurations. In the current configuration the user employs the QMotor interface for the input of desired trajectories for the panel and workstation, system monitoring, etc. (FIGURE 4.56). The user can also perform tasks such as data logging and online gain tuning was performed using Qmotor. It also allows the user to easily swap between different control modes.
4.8.9 Trajectory Planning for Configurations

In realizing the six configurations, real-time trajectory planning of AWE’s panels follows the resolved rate approach based on a conventional Jacobian-based model. In planning the trajectory of the panels, the primary interest was positioning the body (i.e. face) of each panel so that the attached screens or plastic surfaces were oriented to afford the best physical or visual access from the perspective of the user(s). This is in contrast to the serial-link redundancy resolution problem commonly found in the literature where the trajectory relative to the most distal (“end effector” or simply, tip) of the panel is the primary concern of trajectory planning. 23

In the trajectory planning, different guiding modes were explored to improve path choice from one configuration to another. Eight different guiding modes were selected, inspired by the cobra, sequoia ostrich, an elephant’s trunk, and the shape of a football to reflect the perceived “organic” nature of the wall. (FIGURE 4.57)

23 More in this subject can be found in KWOKA, MARTHA: The AWE wall: a novel robotic surface. Thesis (M.S.) Clemson University, 2008. Master Student collaborator in the AWE project. Focused her research in the movement and computer simulation of the wall.
The function of a guiding mode is to resolve the redundancy by providing a “guide” for the wall during a given movement under the trajectory planning strategy.

Figure 4.58 illustrates the motion planning approach viewed as a moving wall section, where the blue line represents the guiding mode (growing lighter with time) and the red line, the desired mode. In the more favorable condition (FIGURE 4.58 left) the guiding mode allows the top and middle joints to move into position, reducing the torque on the bottom motors; whereas, in the less favorable condition (FIGURE 4.58 right), the top joints take longer to move into position, placing more torque on the bottom motors. The configuration show on the left is therefore most favorable, serving as the model for the wall trajectory.
4.9 Usability Test Methods

“Once we delve into the specifics of an active context…the designer may find that the issues are too complicated to understand and act on intuitively; this is when the partnership between designer and a human factors psychologists, becomes essential. The basic complexity of design constrains still demands subconscious synthesis as well as collaboration between everyone in the multidisciplinary team...”
Bill Moggridge; Designing Interactions: p. 654

A usability evaluation of configuration 2 – a single user in composing mode (as presented in section 4.7.2.2, FIGURE 4.39) – was conducted as part of the iterative design cycle. Thus, participants were not able to move AWE’s robotic vertical panels during this test; however, they could adjust manually (by sliding and tilting) the computer monitors.

Since people probably make extensive use of tacit, implicit knowledge when using their workspace during complex, creative tasks (that is, they arrange and grab things on the fly without conscious decision making), AWE’s ease of use could not be
evaluated by relying solely on verbal reports of users or usability experts (as in heuristic evaluation). Instead, AWE was evaluated by conducting a usability test; in which participants performed representative tasks using AWE while analysts observed and recorded their behavior. However, the representative tasks for this usability test were different from those of most usability tests, because, for work tasks, AWE is designed to facilitate long-term tasks where users access large amounts of multimodal information and then integrate this information into a creative product. Therefore, in this usability test, participants – advanced undergraduate and graduate architecture students – create preliminary designs for a multifamily residence. Thus, the participants performed only one 2-hour task during the test, while working individually and verbalizing their thoughts. Using videotaping and a real-time coding program (FIGURE 4.59), it recorded user’s focus of attention within the AWE workspace throughout the test session. Data analysis focused on spatial and temporal components of how users used the paper and computer displays of AWE.

FIGURE 4.59: Time and region Map software used to collect data on the use of space. This program generated the heat maps presented in the overall use of awe workspace section.
4.9.1 Participants

For the architectural task, the 8 participants (age range 19 to 27; 4 females) were students in an undergraduate or graduate architecture program at Clemson University. All participants were in the 3rd year or higher-level in the program, had previous experience in designing, were familiar with the architectural software required for the design task. For the tax task, the 4 participants (age range 20 to 50; all males) each had between 1 and 15 years’ experience preparing and submitting tax forms to the US Internal Revenue Service (IRS).

4.9.2 Materials and Tasks

The first part of the architectural design task required participants to develop two preliminary design studies for a multifamily residence on a specific site. Each of these consisted of three parts: a reference picture used to guide the design, a perspective drawing, and a 2-dimensional plan drawing. Initial work on the preliminary designs could be done on paper or the computer, but each of the final preliminary designs was required to be included in Photoshop documents on the computer. The second part of the design task (the final design study) required participants to pick one of their preliminary design studies and develop it further by creating a 3D model using CAD software, and then including images from the 3-D model (e.g., front and back view, perspective) in a Photoshop document.

In addition to the AWE workstation (with internet connection), participants were provided with the following materials: 3 manila folders containing paper reference
materials from different architects’ work; printed and computer plans of the building site; paper pictures of the building site; computer 3D model of the building site in Sketchup (CAD) software; Photoshop template documents for the two preliminary design studies and the final study; pads of paper; rolls of tracing paper; and pens.

For the tax task, participants were presented with detailed financial documents for a hypothetical friend, and then completed the IRS tax forms for this person. This required completing the main tax form (1040) and four auxiliary forms. Some tax instructions and blank tax forms were given to the participants on paper; others were available on the web. This task took about 2 hours.

4.9.3 Procedure

Participants were initially instructed in the display surfaces of the AWE workstation and how to adjust it, and the design task and the materials available for the task. Then, participants were asked to provide a verbal report of what they were thinking about whenever they moved to a new step within the task. During the session, an analyst with architecture (or tax) expertise sat near the user (Evaluator 1) and prompted them if they were not providing a verbal protocol, answered their questions about the goals of the task (without providing task help) or how to use the required task software. Another analyst sat out of the participants’ view and took written notes on the users actions and words (Evaluator 2), and also used a software program to code the time and location of changes in the participants’ focus of attention around the workstation. (FIGURE 4.60)
After the task session, participants completed an oral questionnaire concerning the perceived usefulness of each part of the AWE workstation.

**FIGURE 4.60** Schematic render of lab configuration for both performed UT. Participant sits in the workstations to perform the given task, Evaluator 1 sits at the back right of it, takes notes of all actions and engages in the talk-aloud technique with the participant. Evaluator 2 sits in the back covered and analyzes his movements by a TV image from the recording. Only Evaluator 1 can engage in any form of communication with the participant. (Author)

### 4.9.4 Usability Test Findings

For the architectural task, all 8 participants created competent and detailed solutions to all parts of the design problem, taking from 1.5 to 2.5 hours to finish. First data is present on how the participants used the overall AWE workstation, focusing on variables such as overall frequency of using paper vs. computer, how much users spread out paper over the workspace, and whether users’ frequency of using paper vs. computer changed during the task. Then data is presented on how participants used each of the computer and paper display areas of AWE. The subjective questionnaire data are presented in Appendix B and its data agrees with the data presented below.
4.9.4.1 Overall Use of AWE Workspace

Given the architectural task constraints requiring many of the subtasks to be done on the computer and allowing the others to be done either on the computer or paper, an extreme computer-pile could avoid using paper altogether, while an extreme compute-phobe could use paper about 50% of the time. The young age and high computer skills of participants led to expect relatively low paper use. However, the affordances of paper for creative, knowledge-intensive tasks mentioned earlier led us to expect a moderate amount of paper use. On average, participants used the three computer monitors for 71% of their design work and the paper display areas for 29%. Participants showed considerable variability in their frequency of using the computer vs. the paper, falling into three levels of preference for paper: 2 users who used paper for 14% of their work (on average); 5 who used paper for about 32% of the time; and 1 who used paper 44% of the time. Thus, even though task constraints and participants’ computer skills might have minimized use of paper on this task, evidence was found of moderate paper use in most participants. These findings provide further evidence that paper is a key part of knowledge-intensive tasks and support the design goal for AWE of allowing users to integrate paper and computer displays.

Given participants consistent, moderate use of paper, and mentioned earlier how participants sometimes arrange paper spatially within their workspace to meet changing task, the extent to which participants spread out paper across the AWE workspace was investigated. FIGURE 4.61 shows, AWE contained 4 areas for paper display: the vertical area (with 3 locations), the center table (with 5 locations), the left table (with 2 locations),
and the right table (with 3 locations). 3 participants who used all 4 areas and 8 to 11 locations were classified as very high paper spreaders, 2 participants who used 3 areas and 7 to 9 areas as high spreaders, 2 participants who used 2 areas and 6 to 7 areas as low spreaders, and 1 user who used 2 areas and 3 locations as a very low spreader. Thus, 5 of 8 participants (the high and very high spreaders) made extensive use of AWE’s capability for displaying paper. FIGURE 4.61 shows how the AWE workspace was used by one of the very high paper spreaders; and FIGURE 4.62 shows one of the low paper spreaders. As might be expected, participants who used paper more often tended to spread out paper more, as shown by a .75 correlation between the percentage of paper use and the number of paper display areas used.

FIGURE 4.61 Frequency of use of AWE paper and computer display locations for a VERY HIGH paper spreader who used all 4 of AWE’s paper display areas (vertical, center table, left table, right table). Darker fill color indicates more use; white means no use. Heavier border indicates more active use; lighter border indicates storage use.
The preceding analyses studied the use of AWE’s workspaces for computer and paper work by averaging over a lengthy work session. However, participants varied how they used AWE’s workspaces over time, sometimes using only paper displays for long periods (e.g., perusing paper reference materials or sketching ideas), sometimes using only computer displays for long periods (e.g., working in CAD or Photoshop), and sometimes using paper and computer displays together (e.g., creating a CAD model while using a paper sketch as a reference). To help understand these changes, we coded whether each participant used paper only, computer only, or paper and computer together for each of the design subtasks throughout the design session.
The left side of FIGURE 4.63 shows a participant who initially used only paper for examining reference pictures and for sketching design ideas, then used paper and computer together when using the CAD program with a paper sketch as a reference, and finally completed a variety of other design tasks on the computer. This pattern of using paper only, then computer and paper together, and then computer only was seen in 5 of the 8 users. The right side of FIGURE 4.63 shows another of these 5 participants, who repeated the “paper–both–computer” pattern three times during the session. The other 3 of the 8 participants did not follow the “paper–both–computer” pattern. These participants showed little use of paper alone and tended to switch between using only the computer and using paper and computer together. (data on APPENDIX B)
This temporal look at patterns of using AWE supports the conclusion from the spatial analysis—that people performing creative, knowledge intensive tasks regularly switch between paper and computer displays depending on personal preferences and the demands of particular subtasks.

4.9.4.3 Use of Individual Parts of AWE

The final usability data presented deals with how participants used each of the 5 areas of the AWE workstation. For the architectural-task usability test (with 8 participants), TABLE 2 documents usage in terms of the number of participants who used each area and the average percentage of time participants used each area. It also shows whether each area was used primarily for active use, information storage, or both.

<table>
<thead>
<tr>
<th>AWE Area</th>
<th>Architectural Task</th>
<th>Tax Task</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% Using</td>
<td>Main Use</td>
</tr>
<tr>
<td>computer monitors</td>
<td>100</td>
<td>active</td>
</tr>
<tr>
<td>vertical paper</td>
<td>62</td>
<td>storage</td>
</tr>
<tr>
<td>left table</td>
<td>62</td>
<td>storage</td>
</tr>
<tr>
<td>center table</td>
<td>100</td>
<td>active</td>
</tr>
<tr>
<td>right table</td>
<td>87</td>
<td>active</td>
</tr>
</tbody>
</table>

TABLE 2. Use of individual AWE work areas in terms of percentage of users and percentage of time for two usability tasks.
For both tasks, the computer monitors showed heavy use, being used by all participants and accounting for 70% of architectural task time. As mentioned before, this heavy use was partly due to task constraints. Eleven of 12 participants used each of the 3 computer monitors (and the other person used 2). Monitors were used mainly for active use. One participant adjusted AWE by removing the whiteboard from the middle of the lower vertical row (FIGURE 4.62) and moving the two lower monitors together.

Among paper display areas, the center and right tables received heaviest use. Across both tasks, 10 of 12 participants used both of these tables; and for the architectural task, 5 of 8 participants used them for more than 23% of their total task time. These tables were used primarily for active use, with some storage use as well. Most participants (11 of 12) spread out documents across the center table; while fewer (4 of 12) did this for the right table. The main activities accomplished on the center and right tables were sketching, looking at reference pictures and completed sketches, reading tax documents, entering data into tax forms, and information storage. Across both tasks, the left table was used relatively infrequently, by 6 of 12 participants, and mainly for storage use.

Across both tasks, the three vertical paper displays (whiteboard, corkboard, paper display) were used by 8 of 12 participants, but only for a small percentage of participants’ time. This was because these displays were used mostly for information storage. When information is put in a workspace area for storage and only accessed occasionally, the small amount of time interacting with this storage area does not necessarily mean that this information is unimportant to the task. The vertical paper displays were used mainly for
displaying one or more drawings or pictures, writing notes or task reminders on the whiteboard, and arranging tax documents on the corkboard. Notably, the vertical displays were not used for reading small text or sketching, as they did not afford these activities. (Due to late design changes, 4 of the 12 participants had only two vertical display locations, the whiteboard and the corkboard; the other 8 also had a third location where they could post paper notes. Vertical display use seemed to increase when the third location was added.)

4.9.5 Usability Test Summary

Despite task constraints encouraging computer-based work (especially in the architectural task), all participants used paper regularly in both tasks. Many participants made extensive use of AWE’s horizontal tables for spreading out paper spatially. This usability test also documented how people switched between paper, computer, or combined use at different stages of their task. These findings regarding use of mixed media provide quantitative support for the qualitative findings of ethnographic studies of knowledge workers, these described in section 4.3. Findings also support one of AWE’s primary design goals—to facilitate flexible use of paper and digital media.

With regard to the goal of better integrating non-digital displays into knowledge work, the main way in which this first AWE prototype went beyond the traditional workstation was in the vertical non-digital display spaces. Two-thirds of the participants used these displays, but they used them mainly for short-term information storage (“hot storage”) and rarely for active use.
“The question, then, is how we can change the way we interact with our machines to take better advantage of their strengths and virtues, while at the same time eliminating their annoying and sometimes dangerous actions.”
Donald Norman, The Design of Future Things; p: 04

“In our age of technological saturation, response to place becomes the most practical adaptation strategy of all.”
Malcolm McCullough, Digital Ground; p: 213

Working life in a digital society is ambiguous; it is difficult to define concepts of use, function, intention and affordances. The AWE project responds to such ambiguity by accommodating multiple users working with both printed and digital materials in a dynamic reconfigurable work environment. The ambiguity of working life today calls for a critical analysis concerning the role of Architectural Robotics in an increasingly digital society. This chapters offers a critical reflection on: how technologies are manifested in AWE project; how AWE relates to the theoretical realm of robotics and technology use; how we define levels of success in such a research project, and how robotics redefines architecture and architecture education.

5.1 A Broad Analysis of Architectural Robotics

Recent advances in IT and robotics have suggested that we are entering an “Age of Robots”. (GATE 2006, NOCKS 2008) As desktop and laptop computers have become ubiquitous, so robotics will soon be part of our daily life activities. Broadly robotics is defined as “the science of extending human motor capabilities with machines”
and “the science which studies the intelligent connections between perception and action”, suggesting that “the action of a robotic system is entrusted to a locomotion apparatus to move in the environment, and/or to a manipulation apparatus to operate on objects present in the environment.” (SICILIANO AND KHATIB 2008) Or simply as “autonomous systems”. (NORMAN 2008: 162) These definitions become a more commonplace reality by an increasing infrastructure of electrical and mechanical components which are embedded into the built environment, programmable and “intelligent”.

Vitruvius once predicted an anthropomorphic vision for architecture: architectural composition, proportions, scale, and rhythm are extracted from relationships between forms of the parts and the whole of the human body. These body-building analogy became the base of classical architecture from Vitruvius to Alberti, Palladio, Filarete, and Leonardo. This analogy was latter abandoned with the collapse of the classical tradition and the birth of a technologically dependent architecture. With the exception of Le Corbusier Modulor – an attempt to reinsert the body as a system of measurements and proportion – modern architecture was largely concerned with an abstract rational system that not only neglected the human body but also separated perception and experience of technology from social and physical context.

Today there seems to be a return to certain anthropomorphic aspects in architecture through the way of IT and robotics. However this involves incorporating a different metaphor. Where body-building became columns, plans and facades, today the body-building senses, hears, sees, communicates, and moves, and is characterized by
ambiguous and extensive forms which are both rigid and flexible. The body-building is
no longer an aesthetic metaphor of the human body but one related to the actions of our
senses, our nervous systems and our limbs. This prosthetic extension was described by
John McHale: “from the eye, we extend vision, and therefore survival advantages,
through the microscope and telescope, the photo and television camera, and on to
sophisticated systems that record, amplify and related complex visual and aural patterns
of great magnitude…these externalized controls enable [man] to deal with more complex
patterns of information and with the more coordinated operation of his other extended
systems.” (MCHALE 1969: 116)

Robotics is divided into different sub-fields of interest. A leading theme is the
creation of artificial bipeds and humanoids. Researchers in this sub-field, to some extent,
believe that the future for robotics is about literally mimicking parts of human behavior
and intelligence. Here robotics assists in domestic or entertainment situations. Unlike
Architectural Robotics, the field of humanoids fails to consider more environmental
approaches to the interaction across people and their surroundings. Architectural
Robotics is a vehicle to enrich physical places. The argument for Architectural Robotics
is that to support and enhance our everyday life and interaction, we do not need a
replication of ourselves. Architectural Robotics should search for an allied form of
intelligence, one to complement, and not replace us. In an increasingly digital society
where we are saturated with information, Architectural Robotics is responsive to
everyday living in a quieter way.
Intelligence has been applied as domestic help and as entertainment (e.g. the Kasparov vs. Deep Blue historical challenge, where computer defies human; or the AIBO the Robot dog developed by Sony) (FIGURE 5.1) Architectural Robotics is focused instead on enhancing the built environment, to perform actions which static spaces cannot – to enhance everyday activities. Whereas the humanoid creates a ‘chess paradigm’ where IT as entertainer or opponent (master servant relationship), Architectural Robotics affords collaboration across people.

When considering smart or intelligent environments, Architectural Robotics follows Donald Norman’s call for the role of robotics and artificial intelligence: “the smartest things are those that complement human intelligence, rather than try to supersede it.” (NORMAN 2007: 86) AWE facilitates relationships between objects, an interactive dynamic environment.

Architectural Robotics incorporates the notion of body in space, more than a body purely objectified, or strictly utilitarian; a perspective which affords corporal participative experience, and not just a voyeuristic. One Architectural Robotics as such is concerned
with a holistic and expressive condition: holistic is responsive to a larger social and
cultural frame, which recognizes that designing artifacts must be a part of a larger system.
Expressive, Architectural Robotics embodies a system of values; design communicates.
Architectural Robotics is a technology of context: an interactive system focused on users’
expectations of what it is, what it does, when and where its act, and what are the
communicative functions it carries. Different from anthropomorphic, Architecture
Robotics conceals mechanics following Mark Weiser’s prediction for invisible
computing. Architectural Robotics is the ‘disappearing robot’ embedded into the
environment, sensing and exchanging information with users, reacting to environmental
stimuli, changing the architecture space.

Reconfigurable spaces requires a distribution of robotic technologies which
support a negotiable relationship between body configuration and the computation being
employed in the task, or what Paul Dourish call “the relationship of the body to the task”
(DOURISH 2001: 159) This carries “out different aspects of an activity, we may need to
be closer, farther away, or in different orientations to the object of work hand in hand.
We move around, as the task requires.” (DOURISH 2001: 159)
The configuring of space and the configuring of body are carried out in relation to each
other.

This significant transformation in the notion of body, architecture and context
defines as tree key aspects of an Architectural Robotics: (1) the notion of the building as
a robot; (2) the idea that the building assumes spatial configurations based on information
exchange and contextual interactions; and (3) the sense that the environment as a whole is
endowed with both bodily and robotic (e.g. human and artificial) characteristics complementing human action.

5.2 An Analysis of Architectural Robotics Based Specifically on Andrew Feenberg’s Theory of Instrumentalization

“Individual technologies are constructed from just such decontextualized technical elements combined in unique configurations to make specific devices. The process of invention is not purely technical: the abstract technical elements must enter a context of social constrains. Technologies, as developed ensembles of technical elements, are thus greater than the sum of their parts. They meet social criteria of purpose in the very selection and arrangement of the elements from which they are built up.”
Andrew Feenberg, Transforming Technology p. 67

As described by Feenberg developing technologies are not abstractions, but embedded in social practices. AWE’s technical elements are combined to afford new patterns for working life in a digital society. Such human-robotic interaction follows Paul Dourish’s argument that “technology and practice cannot be separated from each other; they are coextensive and will coevolve. Practices develop around technologies, and technologies are adapted and incorporated into practices.” (DOURISH 2001: 204)

According to philosopher Andrew Feenberg, two aspects of technological development – primary and secondary instrumentalization – can describe such states of co-extensiveness and co-evolution. Primary instrumentalization explains the constitution of technical objects and subjects evolving from pure abstracted forms. Secondary instrumentalization describes how objects and subjects become constituted into actual technical networks; how they acquire affordances, functions and practices; how they evolve and become part of context; and how they create meaning. (FEENBERG 2000)
Primary and secondary instrumentalization revolves about the description of eight categories. These categories inform technological properties, concepts and affordances. Moreover these properties describe the possibilities towards an Architectural Robotics, and specifically, a technological artifact such as AWE.

Such an analysis based on Andrew Feenberg’s instrumentalization theory has been previously applied to identify properties and effects of wood frame construction technology. (CAVANAGH 2007) in this study Cavanagh says: “Feenberg’s analytical tool of primary and secondary instrumentalization can identify particular properties and/or effects of the construction system in both its historic and contemporary guises.” (CAVANAGH 2007) According to Feenberg, these categories can describe “the integration of technologies to larger technical systems and nature, and to the symbolic order of ethics and aesthetics, as well as their relation to life and learning processes of workers and users.” (FEENBERG 1999)

Applying Feenberg’s concepts, the initial four categories of primary instrumentalization – decontextualized, reduce, automatize and position - are here ascribed to Architectural Robotics. The second category of instrumentalization integrates these simplified technologies to a natural and social environment. This involves a process, which Heidegger names ‘disclosure’ or ‘revealing’ of a world.

I. Decontextualization: Objects are artificially removed of their context to be integrated into technical systems, or in other words, decontextualized. Initially Architectural Robotics and AWE can only be described by abstracted elements such as: concrete, wood, masonry, wires, sensors, motors, connectors, actuators,
screens, processor, and hard drives. These materials and components, if applied correctly, may become reactive and responsive. This category sets Architectural Robotics in a technical scheme. Its mechanics and tectonics are fragmented, abstracted from any context or use. These appear to the designer as mere technically reactive forms to be applied in the project.

II. Reductionism: The actions and affordances of Architectural Robotics are ‘stripped’ from use and reduced to aspects to be inserted in a technical network. Qualities are simplified and “de-worlded”: The qualities of Architectural Robotics and AWE can read, sense, react, move; open, inflate, grow. The behavior and qualities of Architectural Robotics and AWE are reduced to technical and functional aspects. These technical affordances are isolated from the effects of its action on its objects.

III. Autonomization: Once the technical schemes of AWE and Architectural Robotics acquire autonomous shapes, they react on an abstract level to certain qualities. Materials and qualities react and begin to acquire formal possibilities. Automization defines the early construction of the developing AWE prototype. Aluminum panels are joined with motors and concrete slabs, which define the design phase of the research; much like Newton’s Third Law: In mechanics, every action has an equal and opposed reaction. Actor and objects belong to the same system and so every effect is simultaneously a cause, and every object is simultaneously an object. Architectural Robotics becomes an autonomous force.
subjected to laws of growth. As in open source developments of technical systems.

IV. Positioning: As Architectural Robotics acquires levels of growth and autonomy, it positions itself strategically according to the object, or user, or inhabitant of such space. AWE develops a scale to its users, panels are dimensioned for two side-to-side inhabitants, and tables are positioned to afford specific work conditions. Positioning is concerned with technical action as navigation; the objects tendency to arrive at a desired outcome. By positioning itself strategically with respect to its objects, Architectural Robotics makes its inherent properties accountable to users.

Secondary instrumentalization deals with the integration of abstract concepts of technology and context. It sets the ground in which technique becomes a fundamentally social activity. Perhaps Architectural Robotics follows Heidegger argument that the essence of technology is by no means strictly technological;24 instead, it is the way we perceive and create meaning with it. This condition presumes that we act in the world by exploring opportunities afforded to us to act by technological spaces. These opportunities can be either physical configurations or socially constructed meanings.

V. Systematization: To function as an actual device, isolated or decontextualized, technical objects must be combined with other technical objects and re-embedded in the natural environment. Systematization combines and connects these abstract automatons into a real function. Motors and sensors become real function in

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24 Heidegger argues in his seminal work The question Concerning Technology that . “The essence of technology is by no means anything technological” (Heidegger )
context. Certain angles of the AWE wall afford uses and possibilities. The process of technical systematization is central to designing AWE as a plug-n-play network of digital and printed technologies.

VI. Mediation: Ethical and aesthetic mediations reinsert simplified objects into new social contexts. Some qualities of certain aspects are given not just by functional or aesthetical aspects, but also by rituals of cultural and ethical meanings. In AWE, usability evaluation supports the qualitative findings on studies of knowledge workers and AWE’s primary design goals: to facilitate flexible use of paper and digital media. Mediation remains an essential aspect of the technical process.

VII. Vocation: The subject is no longer isolated from the object, but is transformed by its own relation to them. Vocation describes AWE’s condition in the world: the action and reaction of the panels in real time by the users. Vocation exceeds passive contemplation or external manipulation, involving also the subject and object in an embodied experience. Architectural Robotics moves from the lab and is integrated in the world, becoming part of the everyday experience of architecture. In AWE, vocation calls for attitudes and dispositions of subjects and objects to improve work experiences, emphasizing a responsive background for our actions. Malcolm McCullough describes this relationship as follow: “The more enduring the environment, the more it shapes our expectations without saturating our attention.” (MCCULLOUGH 2004: 52) Architectural Robotics
calls for the “need for more emphasis on lasting backgrounds.” (MCCULLOUGH 2004: 52)

VIII. Initiative: Initiatives are described by characteristics such as openness and playfulness, previously described in chapter 3. In Architecture Robotics, initiative reflects the praxis of cooperation in the coordination of effort and user appropriation of devices and systems for unintended purposes. Initiative can be described by Paul Dourish as action which becomes practice:

“Not only the detail of what people actually do, but also that the action fits into a wider scheme of ongoing activity that makes it meaningful...action is situated within a community of practice, which provides its members with a set of common orientations and expectations, fluid but persistent over time...Any given interaction between user and system is...just one point in a trajectory of interactions between that system and different users.” (DOURISH 2001: 161)

In the case of AWE and Architectural Robotics it is more than creating an authoritarian workplace; instead, it is about working life in a digital society as something open and creative. Beyond the technological affordances, AWE requires systematization, mediation, vocation and initiative. AWE is designed to provide a dynamic structural system, one which allows the space to be reconfigured in real-time. AWE is designed to afford more complete control to people who use it, not systems controlling people.

As Architectural Robotics is an emerging sub-field in IT and design, it presents considerable challenges. A certain visionary dimension confronts the technological possibilities and, so far, few empirical discoveries. This condition suggests a series of
considerations on Architectural Robotics: these should not be treated as something formal or rationalistic, instead a “Symbiotic relationship [which] only occurs when the person is well skilled and the tools are well designed.” (NORMAN 2007: 19) The classical mistake as Andrew Feenberg argues is that “formal thinking considers its objects only in terms of their utility [:] it treats their potentialities as no different from an outcome of a technical manipulation.” (FEENBERG 2002: 169) The unilateral role of function, as a result becomes too dependent and closed; it cannot achieve Umberto Eco’s sense of openness, as considered in chapter 3. As Feenberg further articulates the “conception of value… is itself a product of the abstractive process in which formalism obscures the nature of potentiality.” Potentiality is what makes these objects useful or utilitarian, “transformed, adapted to the dominant social purpose, transcendent toward the realization of their potentialities in the context of a better society.” (FEENBERG 2002: 169)

5.3 Success in Design

The levels of success demonstrated by the usability evaluation (SECTION 4.9) support one of AWE’s primary design goals: to facilitate flexible use of paper and digital media in an articulated responsive environment. In a broader scope, to define success in the process of space making for Architectural Robotics requires a reflective analysis considering technical, design and social criteria. “The fundamental restriction on people’s successful interactions with machines”, Donald Norman suggests, is “the lack of common ground[:;] but systems that avoid this danger, that suggest rather than demand, that allow
people to understand and choose rather than confronting them with unintelligibly actions, are perfectly sensible. (NORMAN 2007: 55)

The research of a novel robotic work environment, due to its experimental nature, presents certain levels of success. Identifying these levels describes the limits and future research directions in Architectural Robotics and the AWE project:

• The programming of robotic structures: The motion planning involved in this process requires specialized kinematics, construction and scripting, and remains a very complex task. Programming of robotic structures falls under seminal issues related to robotics engineering, such as: Dynamics and control; motion planning; object sensing and recognition; studies on actuators, transducers, and transmissions; kinematics; mobile manipulator and platform control; programming kinematic, geometry; relationships between coordinates; and sensors programming. The success of programming robotic structures involves the continuous research and evolution of these described fields.

• Motors, connections, movement and speed. In the case of AWE, the use of rigid-link motor connections – instead of a soft continuum robot – was not so successful in improving levels of dexterity, position, sensing, loading, and real time manipulation of the wall by users. The initial movement proposed for the robot-room and the prototype-3 initial concepts25 where compromised partially by technical possibilities of the motors. These motors allow a playful, responsive

25 Described in Section 4.7
Architectural Robotics; however, due to the size and mechanical difficulties of the motors, AWE’s movement and affordances are somewhat compromised.

- Animation of large elements in the environment: The movement of heavy metal components if not designed properly, can be dangerous to users. “The development of new technologies must eliminate annoying and sometimes dangerous actions” (NORMAN 2008) In the AWE built prototype, sensors were programmed with a security feature – the wall’s ‘breathing mode’. (FIGURE 5.2) When in a close configuration – such as configuration 2, 3 and 4 – the wall senses user’s unintentional and unpredicted movement, and reacts by expanding its panels and moving away. Such a sensing mode was tested successful; it avoided problems of animated, large metal components in the environment.

![FIGURE 5.2: Wall ‘Breathing Mode’ Security feature: walls senses user’s unintentional and unpredicted movement, and react by expanding its panels and moving away avoiding accidents. (Author)](image)

- Simplicity of use: Working life in a digital society demands a design which supports: “augmentative technology should be voluntary, friendly and cooperative.” (NORMAN 2008: 130) To date the AWE’s interface remains overly complex, it cannot solve problems of use with everyday simplicity, and it requires
the development of a user-friendly interface. Moreover, any interactive sequence to be successful must come from a voluntary, user-friendly and cooperative response of circumstances which include expectations about actions, outcome of early actions, new concerns and opportunities.

- High-cost of implementing new technology: One of the negative points of such projects is their high cost of implementation. AWE could only be designed with substantial research funding coming from the likes of National Science Foundation. Such projects remain very expensive. There is always the assumption that such projects will become cheaper once the technology involved becomes ubiquitous and the knowledge involved becomes simpler.

Architectural Robotics suggests that meaning and success arrives from multiple levels – technical, positional, vocational and social. Success in Architectural Robotics comes from not assessing robotics as a formal medium. Instead, the “medium” is the connection between users and its interactions; interactions turn actions into meaning. “The more enduring the environment, the more it shapes our expectations without saturating our attention…we have the need for more emphasis on lasting backgrounds.” (McCullough 2004: 52) Success, in a way, becomes a coextensive relationship, “shared control and shared intelligence” as described Donald Norman. “The Robot does what it does well, and the person what people do well.” (NORMAN 2007: 86) “What determines success at the end of the day is the ability to develop systems that resonate with, rather than restrict [or, worse, refute], the social organization of action.” (DOURISH 2001: 95)
5.4 Architectural Robotics and the Redefinition of Architecture and Architectural Education

The development of Architectural Robotics in the AWE project begins with activities that are somewhat foreign to the architect practicing in the conventional sense: the invention of hypothetical “users” or “inhabitants” engaging the architectural work in real-time “performances.” The concepts of these Architectural Robotics were derived from these envisioned scenarios which defined how architectural works might be engaged by different people under different conditions. Design starts by establishing which possible interactions the spaces may afford, however the level of interaction must be open to new possibilities, and not constrain its use. At the outset of the AWE project, for instance, the research team invented personas and scenarios to establish the proper use of the space.26 As example, a group of such users: a biologist named “Laura,” her young child, her colleagues, and her nephew visiting from Latin America. The members of this invented group of users were then imagined interacting with AWE, individually and in groups, as a vehicle for understanding what AWE might look like and how it might behave in support of human needs. From the outset, the research team was thinking about AWE not as an isolated object but as one aspect of a dynamic, interactive, responsive system that includes AWE’s users and its immediate environment.

While it might be said that architects typically consider how users will engage works of their design, there is a fundamental difference in the case of this Architectural

26 Details on the use of Personas and Scenarios to establish the work configurations and possible user interaction are in Chapter 4
Robotics: the investigators are dealing with a responsive system that is actively engaged by and interacting with the user, rather than a building recognized, wrote Walter Benjamin, “much less through rapt attention than by noticing the object in incidental fashion.” (BENJAMIN 1992) Unlike a conventional building, Architectural Robotics and its users are bound together in a performance by “design.” This makes a Architectural Robotics much more like a cell phone or an automobile than a building: something which produces a multitude program arrangements enabling productive and dynamic interaction between people and objects in the world.

Architectural Robotics must go beyond simplistic formal achievements; it must instead explore ways for improving life, for developing existing places, and for enhancing human interaction. This is not a utopian dream in which technology or architecture transforms completely our everyday reality. Instead, architecture and technology and, here particularly, Architectural Robotics hybrid must support human activity, respond naturally, and perform according to our necessities. Architectural Robotics, when employed, must also complement and redefine our urban living patterns. Answers to life problems and opportunities must not come from a computational or robotic solution itself, but rather through the way these technologies, embedded in architecture, help forward the interaction across people and their surroundings to create places of social and psychological significance. For philosopher Andrew Feenberg, “technology is not simply a means but has become an environment, a way of life.” (FEENBERG 2002, 8) Moreover, he explains this way of life as:

“Technology should not be seen as something distinct from humans and nature because technology is “coemergent” with the social and natural
worlds. Humans, nature, and technologies can only be distinguished theoretically because they have been first distinguished through various practices in which all, not merely the humans among them, engage. “Collectives” or “hybrids” encompassing humans and non-humans…because what we know is a complex of mutuality defining human, natural, and technological dimensions” (FEENBERG 2002: 29)

Clearly, an Architectural Robotics, ‘open, responsive and performative,’ is more than an aesthetic search, a stylistic possibility, or a technological quest; it is, instead, a way to develop new spatial patterns in support of human activities.

To develop new spatial patterns supporting human activities, collaborative teams are required. “The intuitive resolution of contemporary design problems simply lies beyond single individual’s integrative grasp… there are limits to the individual designer’s capacity.” (ALEXANDER 1964: 5) Such collaborative work follows from a basic premise followed by the AWE investigators in concert with the call coming to us from research universities and (to no surprise) the research funding agencies that help support them (e.g. the National Science Foundation and the National Institute of Health): that the complex problems and opportunities for living today warrant investigation by transdisciplinary teams of researchers drawn from different disciplines sufficiently complex in composition to address them. More than multi-disciplinary team work, which merely brings together investigators from various disciplines, “transdisciplinary” teamwork is defined by its members sharing a conceptual framework that integrates and transcends the disciplinary perspectives of individual team members so that each team member develops some reasonable understanding of how the other members, drawn from other disciplines, work. This process resembles with what David Wang entitles
“designer-as-cultivator”, (GROAT AND WANG 2002: 117) the architects role in a collaborative team emphasizes process and encourages transdisciplinary contributions. The cultivation of a transdisciplinary team takes time: more time than many architects have patience for. Transdisciplinary projects have relatively long project cycle (e.g. 3yrs) that might prove frustrating to some architects and architectural faculty members who want relatively quicker outcomes from their efforts.

In a recent *Harvard Design Magazine* article, David Celento argues that architects “invite their extinction” if they fail to “embrace technological innovations” (CELENTO 2007) which potentially open new possibilities for architectural practice. The collaborative research and educational activities just described cultivate in students of architecture new vocabularies and new, complex realms of understanding which promise both novel design propositions and the very survival and even flourishing of architectural practice and architecture.
CHAPTER SIX

CONCLUSION

The full-scale, working prototype of an Animated Work Environment has been guided by a human-centered design approach involving surveys and ethnographic study. Usability tests of the physical prototype were iteratively performed as the AWE prototype was improved. It was observed that AWE benefited participants engaged in the complex tasks (e.g. completing tax forms and engaged in a design activity requiring digital and analog materials and tools). These tests suggest the potential of AWE to support complex human activity involving mixed media and tools.

In supporting the thesis statement and claims, the dissertation has made a number of specific contributions. These include:

- The identification and translation of contemporary work patterns into design possibilities
- The formulation of an extensible method for multidisciplinary design
- The development of an innovative approach to kinetic structures and responsive environments
- The taxonomy of different work interfaces
- The formulation of a methodology for collecting data on users working with both digital and analog material
• The full-scale design fabrication and test of a working prototype supporting working life in a digital society

6.1 Future Directions

The design prototype and evaluation of AWE suggest future research in the areas of human-robotic interaction and sensor networks. More specifically, future work involves: (1) devising a user-friendly interface to change the AWE wall configurations; (2) implementing another cycle of usability testing focused more on user collaboration and on the movement between configurations by asking two participants working together to design and then present a small building as part of an informal, “in-house” design practice activity; (3) Exploring the employment of different sensors working with AWE’s IR’s; (4) Developing an additional component to the AWE system that provides configurability of screens and other drawing and pin-up surfaces in a horizontal orientation, “wrapping around” users seated before the AWE wall in response to the findings from our usability tests. The addition of (4) will allow AWE to ‘wrap-around’ users in both the horizontal as well as the vertical dimensions.
Appendix A

Frame Design

For more information on the AWE project access: www.aweproject.org.

FIGURE A-1: AWE front view with details.
FIGURE A-2: AWE side view with details.
FIGURE A-3: Configuration-1 wall angles

FIGURE A-4: Configuration-2 wall angles
FIGURE A-5: Configuration-3 wall angles

FIGURE A-6: Configuration-4 wall angles
FIGURE A-7: Configuration-6 and 6 wall angles
FIGURE A-8: AWE Horizontal Surfaces
Appendix B

Data summary for AWE usability test (8 architecture task participants)

VARIABLE: COMPUTER-PAPER USE

Definition: overall percentage of time using computer vs. paper

<table>
<thead>
<tr>
<th>Computer-Paper Use Category</th>
<th>ID</th>
<th>% computer</th>
<th>% paper</th>
</tr>
</thead>
<tbody>
<tr>
<td>High computer: 86% C / 14% P</td>
<td>6</td>
<td>88</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>85</td>
<td>15</td>
</tr>
<tr>
<td>Mixed: 68% C / 32% P</td>
<td>7</td>
<td>72</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>71</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>68</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>68</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>63</td>
<td>37</td>
</tr>
<tr>
<td>High Paper: 56% C / 44% P</td>
<td>4</td>
<td>56</td>
<td>44</td>
</tr>
</tbody>
</table>

TABLE B.1: Computer paper use

Conclusion: moderate individual differences in preference for computer vs. paper

VARIABLE: PAPER SPREADING

Definition: degree of using paper at multiple locations both within and across the 4 paper display areas (left desk, center desk, right desk, vertical paper displays including whiteboard. Each area had 2 to 5 locations.
### Table B.2: Paper Spreading

Usage maps showing the frequency of use of the 13 paper display areas are shown on the next two pages for one example of Very High spread (ID 3) and one example of Low spread (ID 1).

Conclusion: wide individual differences in use of paper display areas, from concentrating paper use within only 3 of 13 locations and 2 of 4 areas, to spreading out paper across most of the locations and all 4 areas.

<table>
<thead>
<tr>
<th>Paper Spreading Category</th>
<th>ID</th>
<th># of 4 areas used</th>
<th># of 13 locations used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very high spread</td>
<td>3</td>
<td>4</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>4</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>High spread</td>
<td>2</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>Low spread</td>
<td>6</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Very low spread</td>
<td>7</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

### Table B.3 Comparison of Computer-Paper Use and Paper Spreading

<table>
<thead>
<tr>
<th>Computer-Paper Use</th>
<th>ID</th>
<th>Paper Spreading</th>
</tr>
</thead>
<tbody>
<tr>
<td>High computer: 86% C / 14% P</td>
<td>1, 6</td>
<td>Low</td>
</tr>
<tr>
<td>Mixed: 68% C / 32% P</td>
<td>7</td>
<td>Very low</td>
</tr>
<tr>
<td>High Paper: 56% C / 44% P</td>
<td>4</td>
<td>Very high</td>
</tr>
</tbody>
</table>

TABLE B.3 Comparison of Computer-Paper Use and Paper Spreading
Conclusion: low paper users tend to spread out paper less, while high paper users tend to spread out paper more. Evidence for this is the large positive ($r = .75$) correlation between the amount of time spent using paper and the number of the 4 workspace areas used for paper display.

**VARIABLE: CHANGE IN USE OF COMPUTER VS. PAPER OVER TIME**

The diagrams below show three patterns in how participants changed over the course of a session in terms of how they used paper-only vs. computer-only vs. both together. Paper use only is shown by a solid white horizontal band; computer use only is shown by a solid blue horizontal band; using both together is shown by a blue & white horizontal band.

**PATTERN 1 – PAPER TO COMPUTER, SINGLE TRANSITION (N = 4)**

The left pattern (participant ID 5) shows exclusive paper use early in the session (e.g., for perusing reference books and sketching), then a transition to simultaneous computer and paper use (e.g., using paper as a reference while creating something on the computer), and finally exclusive use of the computer (e.g., creating the final architectural products using CAD and photoshop). This pattern was followed by 4 participants (IDs: 4, 5, 6, 8).

**PATTERN 2 – PAPER TO COMPUTER, MULTIPLE TRANSITIONS (N = 1)**
The center pattern (ID 3) shows that this first pattern of paper, then computer with paper, then computer is repeated three times (assuming one ignores a short, inconsequential period of computer at the very beginning). This pattern was only followed by 1 participant (ID 3).

PATTERN 3 – SHARED COMPUTER AND PAPER USE (N = 3)

The right pattern (ID 1) shows a pattern of either shared computer and paper use or exclusive computer use, with little use of paper alone. This pattern was followed by 3 participants (ID 1, 2, 7).

FIGURE B-1: Shared Computer and Paper Use (author)
USE OF INDIVIDUAL WORKSPACE AREAS

<table>
<thead>
<tr>
<th>Workspace Area</th>
<th>Mean Use</th>
<th>Minimum Use</th>
<th>Maximum Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>computer monitors (3)</td>
<td>70</td>
<td>54</td>
<td>87</td>
</tr>
<tr>
<td>vertical paper display locations (3)</td>
<td>0.5</td>
<td>0.0</td>
<td>2.1</td>
</tr>
<tr>
<td>left table locations (2)</td>
<td>0.3</td>
<td>0.0</td>
<td>1.0</td>
</tr>
<tr>
<td>center table locations (5)</td>
<td>21</td>
<td>9</td>
<td>33</td>
</tr>
<tr>
<td>right table locations (3)</td>
<td>4.1</td>
<td>0.0</td>
<td>20.8</td>
</tr>
<tr>
<td>hand or lap</td>
<td>2.5</td>
<td>0.3</td>
<td>9.2</td>
</tr>
</tbody>
</table>

TABLE B.4: Variable: percentage of total task time using individual workspace areas

Conclusion: Given that the constraints of the task required high computer use, the very frequent computer use (70%) was not surprising. Of the 4 paper display areas, the center table was used frequently (21%), the right table occasionally (4%) and the vertical displays and left table hardly at all (< 1%). Viewing paper in the hand or lap was done occasionally (and about 9% of total time for one person).

THREE COMPUTER MONITORS – PATTERNS OF USE

All 8 participants used all 3 monitors; 6 of 8 had a single primary monitor; they used this monitor more than 45% of their total task time. For 5 of these 6, this was the lower left monitor, for 1, this was the upper left monitor, 2 of 8 had two primary monitors, for both, these were the 2 lower monitors. Monitors were used primarily for active use, not information storage. One participant moved the whiteboard out of the way and then moved the 2 lower monitors together.
THREE VERTICAL PAPER DISPLAY LOCATION (CORKBOARD, WHITEBOARD, PAPER DISPLAY) – PATTERNS OF USE

3 of 8 used 0 of the 3 vertical paper display locations, 4 of 8 used 1 of these, 2 used whiteboard, 1 for storage, 1 for active use, 1 used paper display for active/storage use, 1 used corkboard for storage, 1 of 8 used 2 of these, 1 used corkboard and paper display for storage.

CENTER TABLE – PATTERNS OF USE

Preference for spreading paper out
7 of 8 used 4 or 5 of the 5 locations, indicating spreading paper out, 1 of 8 used only 2 of the 5 locations, indicating concentrating paper.

Mostly for active use
7 of 8 used center table mainly for active or active/storage use, 1 of 8 used the 3 center locations for active or active storage use; and the 2 outside locations for storage.
FIGURE B-2: Heat maps of architecture task (author)
### TABLE B.5: Debriefing: Qualitative Questionnaire

<table>
<thead>
<tr>
<th>Question</th>
<th>Nate/Henrique</th>
</tr>
</thead>
<tbody>
<tr>
<td>re 3 screens</td>
<td>3 preferred the lower monitors over the upper 1 monitor, 2 liked the two left screens, 2 liked not having to minimize windows, 1 thought three screens was overkill for the task and could get confusing</td>
</tr>
<tr>
<td>2. What # of screens would you use regularly</td>
<td>4 one screen; 2 two screens; 2 three screens</td>
</tr>
<tr>
<td>3. Was the arrangement ok</td>
<td>4 preferred 3 in a row horizontal; 1 for three in a row vertical, 1 for backward L. 1 preferred only 2 screens with more space to hang things, 1 liked the L arrangement.</td>
</tr>
<tr>
<td>4. Adjustability ok?</td>
<td>Most said OK and most did not have to adjust. 1 was not comfortable adjusting. 1 felt upper screen was hard to move.</td>
</tr>
<tr>
<td>5. Close enough?</td>
<td>6 yes; 1 closer to person, 1 closer together (screens)</td>
</tr>
<tr>
<td>re horizontal space</td>
<td></td>
</tr>
<tr>
<td>1. How useful</td>
<td>8 found overall horizontal space useful</td>
</tr>
<tr>
<td>2. Enough desk space?</td>
<td>8 yes</td>
</tr>
<tr>
<td>3. Layout ok?</td>
<td>4 liked current arrangement</td>
</tr>
<tr>
<td>re vertical space</td>
<td></td>
</tr>
<tr>
<td>1. How useful</td>
<td>8 said not useful at all; 1 said it might be more useful for a longer task; 1 said you couldn't tell it was magnetic; 1 said need to be able to pin stuff up; 2 said that it was too far away:</td>
</tr>
<tr>
<td>2. What # of display spaces would you use regularly</td>
<td>5 0's or 0 to 1's; 2 always pins stuff up (especially if project is larger)</td>
</tr>
<tr>
<td>3. Arrangement ok?</td>
<td>6 said arrangement ok; 1 prefers corkboard; 1 would put monitors closer together</td>
</tr>
<tr>
<td>4. Close enough?</td>
<td>7 yes; 1 arch overhead more</td>
</tr>
</tbody>
</table>
Appendix C

AWE .cpp Script

#include "stdafx.h"
#include "AWEprotoype2.h"
#define imagevisible 1 //1=true (yes), 0=false (no), 2=only for saving, do not show
#define userinfo 2 //0=get no info, 1=hold links still, 2=rails

void AWEproject(char const *picture, int choice,int choice2,int choice3, double n_scalar)//F1
{
    int pconfigs=13; //number of possible configurations
    //load picture and get its info
    ImgGray INimage;// INimage2;
    Load(picture,&INimage);
    int w = INimage.Width();
    int h = INimage.Height();
    int maxit=14000;//max number of itterations
    int printit=maxit/100; //number of itterations before the display refreshes
    //open up two files for writing in
    FILE *FileO2,*FileO9,*FileO10,*FileO12,*FileO8, *FileO11;
    CString
    OutFileName2,OutFileName10, image1, image2, OutFileName12, OutFileName8, OutFileName11;
    image1.Format("data/i_progression%dto%dby%d_%d.jpg", choice,
                   choice2,choice3,(int)(n_scalar*100));
    image2.Format("data/i_result%dto%dby%d_%d.jpg", choice,
                   choice2,choice3,(int)(n_scalar*100));
    OutFileName2.Format("data/mkwoka_q_%dto%dby%d_%d.txt", choice,
                  choice2,choice3,(int)(n_scalar*100));
    OutFileName10.Format("data/AWE_distxy_out%dto%dby%d_%d.txt", choice,
                 choice2,choice3,(int)(n_scalar*100));
    OutFileName12.Format("data/Torque%dto%dby%d_%d.txt", choice,
                  choice2,choice3,(int)(n_scalar*100));
    FileO2 = fopen(OutFileName2,"w");
    FileO10 = fopen(OutFileName10,"w");
    FileO12 = fopen(OutFileName12,"w");
    FileO9 = fopen("D:/marthak/AWEprotoype2/AWEconfig.txt","r");
innumlinks=0,i, rlink=0;
/info from the user
if(userinfo==1)
numlinks=holdorientation();//F10
if(userinfo==2)
rlink=holdrail(numlinks);
numlinks++;
MatDbl link(1,numlinks);
numlinks--;
for(i=0; i<numlinks && rlink==0; i++)//shouldnt happen for numlinks==0
{
    do{
        printf("which link would you like to be held still(1-8)?\n");
        scanf("%lf", &link(0,i));
    } while(link(0,i)<1 && link(0,i)>8);
}
const int Jwidth = 8; //number of joints (1-8)
const int Jheight = 2 + numlinks; //number of dimensions (2+)
const int lines = 3; //number of lines to print on
output image
//output image setup
ImgBgr OUTbgr(w,h);
Set(&OUTbgr, Bgr(255,255,255));
ImgBgr OUTbgr2(w,h);
Set(&OUTbgr2, Bgr(255,255,255));
Figure figOUT("Output Image");
Figure figOUT2("Output Image 2");
if(imagevisible!=1)//hide figure if it is not going to be in use
{
    figOUT.SetVisible(0);
    figOUT2.SetVisible(0);
}
figOUT2.SetVisible(0);
MatDbl q(1,Jwidth); //joint angles
MatDbl qf(1,Jwidth); //final joint angles
MatDbl qr(1,Jwidth); //reference joint angles
MatDbl qdot(1,Jwidth); //joint velocities
MatDbl temp1(1,Jwidth);
MatDbl temp2(1,Jwidth);
MatDbl x(1,Jheight); //end effector positions
MatDbl xdot(1,Jheight); //end effector velocities
MatDbl J(Jwidth, Jheight); // jacobian
MatDbl Jplus(Jheight, Jwidth); // pseudoinverse of the jacobian
MatDbl epsilon(1, Jwidth); Set(&epsilon, 0); // arbitrary input used in qdot.
MatDbl epsilon2(1, Jwidth); Set(&epsilon2, 0); // arbitrary input used in qdot.
MatDbl I; Eye(Jwidth, &I); // identity matrix with dimensions Jwidth x Jwidth
MatDbl inconfig(Jwidth, pconfigs);
MatDbl printpretty(2, Jwidth);
MatDbl sumtheta(Jwidth, 3); // summation of q, qf, qr. summation of thetas array.
theta[2] = theta1 + theta2
MatDbl Kappa(Jwidth, Jwidth); Set(&Kappa, 0);
MatDbl dpoint(2, lines); // double point -- so as to reduce rounding error (x/y, reg/final/ref)
MatDbl torquestat(2, Jwidth);
MatDbl torque(Jwidth, maxit);
CPoint point(0, 0);
TextDrawer OutputText(15, 2);

double c = pi/180, deltaT = .01, xtemp, xmax;
int len[Jwidth]; // length array
int y = 0, itter, quit = 0, color = 0;
char Itter_text[6];
Point drawpoint[lines*2]; // start and end point per section
xdot(0, 0) = 0; xdot(0, 1) = 0; // initialize xdot
if (Jheight > 2)
for (i = 2; i < Jheight; i++)
xdot(0, i) = 0;
for (i = 0; i < pconfigs; i++) // get configuration possibilities from file
for (int j = 0; j < Jwidth; j++)
 fscanf(FileO9, "%lf", &inconfig(j, i));
for (i = 0; i < Jwidth; i++) // initialize joint angles and length of robot parts
{
q(0, i) = inconfig(i, choice-1) * c;
qf(0, i) = inconfig(i, choice2-1) * c;
qr(0, i) = inconfig(i, choice3-1) * c/(q(0, i) + qf(0, i))/2;
q(0, i) = checkbounds(q(0, i), i);
qf(0, i) = checkbounds(qf(0, i), i);
qr(0, i) = checkbounds(qr(0, i), i);
Kappa(i,i)=.1; //create a diagonal matrix of K
qdot(0,i) = 0;
if(i==0 ||i==1)
len[i]=80; //40 cm*2(scaling)
else
len[i]=60; //30 cm*2(scaling)
q(0,i)=checkposition(sumtheta,0,i,len, q(0,i));
qf(0,i)=checkposition(sumtheta,1,i,len,qf(0,i));
qr(0,i)=checkposition(sumtheta,2,i,len,qr(0,i));
if(i==0)
{
sumtheta(i,0)=q(0,i);
sumtheta(i,1)=qf(0,i);
sumtheta(i,2)=qr(0,i);
}
else
{
sumtheta(i,0)= fmod(sumtheta(i-1,0) + q(0,i),2*pi);
sumtheta(i,1)= fmod(sumtheta(i-1,1) + qf(0,i),2*pi);
sumtheta(i,2)= fmod(sumtheta(i-1,2) + qr(0,i),2*pi);
}
for(itter=0; itter<maxit && quit==0; itter++) //for 80000 itterations
{
if(itter%printit==0)//1500
{
color+=2; //for 1500
for(i=0; i<Jwidth; i++)
{
for(int j=0; i==0 && j<lines; j++)
{
if(itter%printit==0)
{
drawpoint[j*2].x=2*w/3;//startpr.x j*2
because only want start points to be initialized
drawpoint[j*2].y=2*h/3;//startpr.y
}
dpoint(0,j)=0;//(x,reg/final/ref)
dpoint(1,j)=0;//(y,reg/final/ref)
}
if(itter%printit==0)
printimage(i,sumtheta, len, drawpoint,dpoint,
lines);//F8
else
printimageb(i,sumtheta, len, dpoint, lines);//F8b
if(itter%printit==0)
{
if(maxit<=itter+printit)
{
DrawLine(drawpoint[0],drawpoint[1],
&OUTbgr2, Bgr(0,0,254), 2);//startp,endp,
DrawLine(drawpoint[2],drawpoint[3],
&OUTbgr2, Bgr(0,254,0), 2);//startpf,endpf
DrawLine(drawpoint[4],drawpoint[5],
&OUTbgr2, Bgr(254,0,0), 2);//startpr,endpr
DrawLine(drawpoint[0],drawpoint[1],
&OUTbgr, Bgr(0,0,254), 2);//startp,endp,
DrawLine(drawpoint[2],drawpoint[3],
&OUTbgr, Bgr(100,100,100), 2);//startpf,endpf
DrawLine(drawpoint[4],drawpoint[5],
&OUTbgr, Bgr(254,0,0), 2);//startpr,endpr
}
else
{
if(itter==0)
DrawLine(drawpoint[0],drawpoint[1], &OUTbgr2, Bgr(0,54+color,0),
2);//startp,endp,
DrawLine(drawpoint[0],drawpoint[1],
&OUTbgr, Bgr(0,54+color,0), 2);//startp,endp,
DrawLine(drawpoint[2],drawpoint[3],
&OUTbgr, Bgr(100,100,100), 2);//startpf,endpf
DrawLine(drawpoint[4],drawpoint[5],
&OUTbgr, Bgr(254,0,0), 2);//startpr,endpr
}
if(i==rlink && rlink>0)
DrawCircle(drawpoint[0],3, &OUTbgr,
Bgr(0,0,255),4);
}
printpretty(0,i)=round(dpoint(0,0)/2);//dpoint(x,reg)
printpretty(1,i)=round(dpoint(1,0)/2);//dpoint(y,reg)
GetTorque(Jwidth, itter, len, printpretty, torque,torquestat);
for(i=0;i<Jwidth; i++)
{
if(i==0)
{
fprintf(FileO10,"%4d\t%d\t%d",itter,
(int)printpretty(0,i), (int)printpretty(1,i));
fprintf(FileO12,"%4d\t%d\t%d",itter,
(int)torque(i,itter), (int)torque(i,itter));
}
else if(i != Jwidth-1)
{
fprintf(FileO10,"\t%d\t%d",(int)printpretty(0,i)-
(int)printpretty(0,i-1),(int)printpretty(1,i)-(int)printpretty(1,i-1));
fprintf(FileO12,"\t%d\t%d",(int)torque(i,itter),(int)torque(i,itter));
}
else
{
fprintf(FileO10,"\t%d\t%d n",(int)printpretty(0,i)-
(int)printpretty(0,i-1),(int)printpretty(1,i)-(int)printpretty(1,i-1));
fprintf(FileO12,"\t%d\t%d n",(int)torque(i,itter),(int)torque(i,itter));
}
}
}xtemp=(fabs(dpoint(0,0)-dpoint(0,1))+fabs(dpoint(1,0)-
dpoint(1,1)))/4;//|x-xf| + |y-yf|
if (itter==0)
xmax=xtemp;
xdot(0,0)=(dpoint(0,1)-dpoint(0,0))/xtemp;
xdot(0,1)=(dpoint(1,1)-dpoint(1,0))/xtemp;//(x/y,reg/final/ref)
}Set(&J,0); //clear Jacobian
for(i=0; i<Jwidth; i++) //set Jacobian
{
for(int n=i; n<Jwidth; n++)
{
J(i,0)-=len[n]*sin(sumtheta(n,0));//J(0,0)=-A1S1-
A2S12...AJheightS1_thru_height
J(i,1)+=len[n]*cos(sumtheta(n,0));
if(rlink>i) //holding in rails (if rlink >0)
\{
  if(n==rlink-1)
  J(i,2)=J(i,0);
\}
else if (rlink>0)
J(i,2)=0;
\}
for(int k=0; Jheight>2 && (k<Jheight-2) && rlink==0; k++)
{ 
  if(link(0,k)>i)
J(i,k+2)=1;
else
J(i,k+2)=0;
\}
double scalar=(xmax-xtemp)/xmax;//(itter)/(double)maxit;
double scalar1=(1-scalar) - n_scalar;/.25;//range .75 to 0
double scalar2= scalar + n_scalar;/.25;//range .25 to 1
if(scalar1<0)
{ 
  scalar1=0;
  scalar2=1;
}\}
for(i=0;i<Jwidth;i++)
temp1(0,i)=(scalar1)*(sumtheta(i,2)-sumtheta(i,0));//sumthetar\sumtheta
for(i=0;i<Jwidth;i++)
temp2(0,i)=(scalar2)*(sumtheta(i,1)-sumtheta(i,0));//sumthetaf\sumtheta
epsilon=Kappa*temp1;//(qr-q);
epsilon2=Kappa*temp2;
getJplus(&J,Jplus);//getJplus(&J,Jplus, FileO3, FileO4);
qdot = Jplus * xdot + (I-(Jplus*J))*(epsilon+epsilon2);
double Xcheck=0,Ycheck=0;
for(i=0; i<Jwidth; i++)
{ 
  //euler's integration could also use runge-Kutta integration if this 
  isnt working
  //get new q
  q(0,i)=q(0,i)+ qdot(0,i)*deltaT;
  q(0,i)=checkbounds(q(0,i),i);
  q(0,i)=checkposition(sumtheta,0,i,len,q(0,i));
if(i==0)
{
    sumtheta(i,0)=q(0,i);
    //fprintf(FileO7,"\n%lf",sumtheta(i,0));
}
else
{
    sumtheta(i,0)= fmod(sumtheta(i-1,0) + q(0,i), 2*pi);//sumtheta[2]= theta0+theta1+theta2
    //fprintf(FileO7,"\t%lf",sumtheta(i,0));
}
if(i==Jwidth-1)
{
    fprintf(FileO2,"%lf\n",q(0,i));//in radians *180/pi);
}
else
{
    fprintf(FileO2,"%lf\t",q(0,i));//in radians*180/pi);
}
//show on screen
if(imagevisible)
{
    if((itter==0 || maxit<=itter+printit))
        figOUT2.Draw(OUTbgr2);
    if(itter %printit==0)//1500
    {
        sprintf(Itter_text,"%d",itter);
        figOUT.Draw(OUTbgr);
        OutputText.DrawText(&OUTbgr, Itter_text, point,
            Bgr(100,100,100),Bgr(0,0,255));
        //while(!figOUT.TestMouseClick()) { }; 
    }
}
if(maxit==itter+1 && (imagevisible==0 || imagevisible==2))
{
    Save(OUTbgr, image1, "jpg");
    Save(OUTbgr2, image2, "jpg");
}
for(i=0; i<Jwidth; i++)
{
forquestat(0,i)=torquestat(0,i)/(maxit/printit);
}

fprintf(FileO12,"average torque\t%lf\t%lf\t%lf\t%lf%lf\n",
torquestat(0,0),torquestat(0,1),torquestat(0,2),torquestat(0,3),torquestat(0,4),
torquestat(0,5),torquestat(0,6),torquestat(0,7));

fprintf(FileO12,"max torque\t%lf\t%lf\t%lf\t%lf%lf%lf%lf\\n",
torquestat(1,0),torquestat(1,1),torquestat(1,2),torquestat(1,3),torquestat(1,4),
torquestat(1,5),torquestat(1,6),torquestat(1,7));
}

int count=0;
double diff;
//singularity check
for(i=0; (i<Jwidth-1||count+1>i) && itter>800 ; i++)//||count<i-2 & itter>800
{
diff=fabs(sumtheta(i,0)-sumtheta(i+1,0));
if(diff<(1*pi/180))
count++;
}

if(count==Jwidth-1 || (Jheight>2 && count==Jwidth-2) )
{
printf("At a singularity 1 degrees diff\n");
quit=1;
}

torquestat=torquestat/sums
diff=diff/(1*pi/180)

void getJplus(MatDbl *mat, MatDbl &matplus)//F2
{
MatDbl J(Jwidth,Jheight);
const int Jwidth= mat->Width();
const int Jheight= mat->Height();
MatDbl J;
J=*mat;
MatDb Jt(Jheight,Jwidth), JJti(Jheight,Jheight), JJt(Jheight,Jheight);
Transpose(J,&Jt);
JJt= J *Jt;
Inverse(JJt, &JJti);
matplus =Jt*JJti;
return;
}
int round(double num)//F6
{
int intnum=num;
int roundnum=intnum;
if((num-intnum)>=.5)//if remainder's abs>=.5
roundnum=intnum+1;
if((num-intnum)<=-.5)//if remainder's abs>=.5
roundnum=intnum-1;
return roundnum;
}
double checkbounds(double angle, int joint)//F7
{
double modangle;
modangle=fmod(angle, (2*pi));
//if(modangle != angle)
// printf("error with angle...going over 360");
if(modangle<0)
modangle+=2*pi;
//if it is starting to get past the bounds of the hinge make it stop
/* if(joint==0)
{
if(modangle>3*pi/2)
modangle=0;
else if(modangle >pi)
modangle=pi;
}
else */if(modangle>140*pi/180)
{
//both have 10 degrees leeway so that slippage isn't such a big deal
if(modangle<205*pi/180)
modangle=140*pi/180;
else if(modangle<270*pi/180)
modangle=270*pi/180;
return modangle;
}

double checkposition(MatDbl &sumtheta, int fig, int joint, int *len, double qorig) {
    double x = 0, y = 0;
    double q;
    joint--;
    if((joint>=0 && sumtheta(joint,fig)+qorig>pi) || (qorig>pi && joint<0)) {
        joint++;
        for(int i = 0; i < joint; i++) {
            x += cos(sumtheta(i,fig))*(len[i]); // x start for your joint
            y += sin(sumtheta(i,fig))*(len[i]); // y start for your joint
        }
        if(joint>0) // i = joint
            x += cos(sumtheta(i-1,fig)+qorig)*(len[i]); // info hasn't been put into sumtheta[i] yet
        y += sin(sumtheta(i-1,fig)+qorig)*(len[i]); // but it will be sumtheta(i-1,fig)+qorig
    } else {
        x = cos(qorig)*len[i]; // if joint == 0 make sure that you are not past pi rad.
        y = sin(qorig)*len[i];
    }
    if(y < 0) {
        double xold, yold; // issues
        if(joint>0) {
            yold = y - sin(sumtheta(i-1,fig)+qorig)*(len[i]);
            xold = x - cos(sumtheta(i-1,fig)+qorig)*(len[i]);
        } else {
            yold = y - sin(qorig)*len[i];
        }
    }
xold=x-cos(qorig)*len[i];
}
q=asin(-yold/len[joint])://y=0=yold+len[joint]*q
if(xold-x>0)
{
    q=pi-q;
}
if(i>0)
q=checkbounds(q-sumtheta(i-1,fig),joint);
else
    q=qorig;
else
    q=qorig;
return q;
}

void printimage(int i,MatDbl &sumtheta,int *len, Point *drawpoint, MatDbl &endp, int lines)//F8
{
    MatDbl start(2,lines);//0=x,1=y and 0=current pos, 1=final pos, 2=ref pos
    int j;
    for(j=0; j<lines; j++)
    {
        start(0,j)=endp(0,j);//(x,reg/final/ref)
        start(1,j)=endp(1,j);//(y,reg/final/ref)
        if(i>0)
            drawpoint[j*2]=drawpoint[j*2+1];//start=endp,0,2,4=1,3,5
        endp(0,j)=len[i]*cos(sumtheta(i,j));
        endp(1,j)=len[i]*sin(sumtheta(i,j));
        drawpoint[j*2+1].x=round(endp(0,j));//left is negative, right is positive*20
        drawpoint[j*2+1].y=round(-endp(1,j));//up is negative, down is positive*20
    }
    for(j=0; j<lines; j++)
    {
        drawpoint[j*2+1]+=drawpoint[j*2];//endp += startp;
        endp(0,j) += start(0,j);
        endp(1,j) += start(1,j);
    }
return ;//drawpoint
}
void printimageb(int i, MatDb1 &sumtheta, int *len, MatDb1 &endp, int lines)//F8b
{
  MatDb1 start(2,lines);//0=x, 1=y and 0=current pos, 1=final pos, 2=ref pos
  int j;
  for(j=0; j<lines; j++)
  {
    start(0,j)=endp(0,j);//(x,reg/final/ref)
    start(1,j)=endp(1,j);//(y,reg/final/ref)
    endp(0,j)=len[i]*cos(sumtheta(i,j));
    endp(1,j)=len[i]*sin(sumtheta(i,j));
  }
  for(j=0; j<lines; j++)
  {
    endp(0,j) += start(0,j);
    endp(1,j) += start(1,j);
  }
  return ;//drawpoint
}
int holdrail(int &numlinks)//F9
{
  int rlink=0;
  do{
    printf("do you want any link to be in the rails? no={0} yes={1-8} ");
    scanf("%d", &rlink);
  } while (rlink<0 || rlink>8);
  if(rlink>0)
    numlinks++;
  return rlink;
}
int holdorientation()//F10
{
  int numlinks=0;
  do{
    printf("how many links would you like to hold orientation for?");
    scanf("%d", &numlinks);
    while(numlinks<0 || numlinks>5);
  } while(numlinks<0 || numlinks>5);
  return numlinks;
}
void GetTorque(int Jwidth, int itter, int *len, MatDb &printpretty, MatDb &torque, MatDb &torquestat)
{
    int i;
    double weight[8];
    double CoGx, CoGy, oldCoGx, oldCoGy;
    for(i=0; i<Jwidth; i++)
        weight[i]=44.48;
    for(i=0; i<Jwidth; i++)
    {
        int j=Jwidth-1-i;
        if(i==0)
        {
            torque(j, itter)=0.5*len[i]/20*cos(atan((-printpretty(1,j)/printpretty(0,j))))*weight[i];
            CoGx=(1.5*printpretty(0,j)+.5*printpretty(0,j))/200;//center of gravity in the x plane
            oldCoGy=(1.5*printpretty(1,j)+.5*printpretty(0,j))/200;
            CoGy=fabs(oldCoGy);//same in the y plane
        }
        else
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