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DIGITALLY-DRIVEN ARCHITECTURE

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Contents

Digitally-Driven Architecture

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The shift from mechanical to digital forces architects to reposition themselves: Architects generate digital information, which can be used not only in designing and fabricating building components but also in embedding behaviours into buildings. This implies that, similar to the way that industrial design and fabrication with its concepts of standardisation and serial production influenced modernist architecture, digital design and fabrication influences contemporary architecture. While standardisation focused on processes of rationalisation of form, mass-customisation as a new paradigm that replaces mass-production, addresses non-standard, complex, and flexible designs. Furthermore, knowledge about the designed object can be encoded in digital data pertaining not just to the geometry of a design but also to its physical or other behaviours within an environment. Digitally-driven architecture implies, therefore, not only digitally-designed and fabricated architecture, it also implies architecture - built form - that can be controlled, actuated, and animated by digital means.

In this context, this sixth *Footprint* issue examines the influence of digital means as pragmatic and conceptual instruments for actuating architecture. The focus is not so much on computer-based systems for the development of architectural designs, but on architecture incorporating digital control, sensing, actuating, or other mechanisms that enable buildings to interact with their users and surroundings in real time in the real world through physical or sensory change and variation.

Digitally-driven architecture points to a paradigm shift from inanimate towards animate structures. Consider, for instance, the nodes of a networked structure pertaining to a building as being a distributed system of digitally-driven sensor-actuator devices. The resulting behaviours of this 'swarm' of digitally-driven devices can allow for a flexible and dynamic range of shapes and geometries within a building, even changes in materials or sensory behaviours, within varying time frames. These behaviours might be programmed to address a multitude of needs or goals from personal to societal, from aesthetic to functional, from emotional to environmental.

Flexibility and dynamic change of shape might, for example, address a range of time-sensitive issues: from local issues relating to the inefficient use of built space to global issues relating to catastrophic conditions or rapid urbanisation.[1] On a local scale, inefficient use of built space results from mono-functioning neighbourhoods such as ones comprised of office buildings that are deserted at night and residential neighbourhoods that are deserted during the day. On a global scale, natural disasters and other catastrophic or emergency conditions caused by earthquakes, hurricanes, war, and so on often result in population migrations as communities abandon their homes and seek shelter elsewhere. Also on a global scale, rapid urbanisation implies the need to address the problem of potential over-population and increased housing demands at urban and architectural levels. For all of these situations, new solutions might be found in digitally-driven reconfigurable, extensible, or resizable structures that permit multiple, rapidly changing, and adaptable uses.

Digitally-driven architecture, as defined here, embraces a wide spectrum of design possibilities and nomenclatures - kinetic, adaptive, responsive, intelligent, interactive, and more. As the authors in this issue point out, the foundations for much of the work that comes under these headings today can be traced back to the mid-20th century work of cyberneticians on systems adapting to continuous feedback from the environment. Then in the 1960s, cybernetic ideas were taken up in Archigram's vision of indeterminate architecture - architecture that could respond to open-ended and uncertain conditions. In the 1970s, Zuk and Clark[2] attempted to introduce physicality to earlier theoretical propositions with their proposals for a new, kinetic architecture. They imagined transformable buildings able to change their physical geometries: auditoriums and stadiums with movable seating and retractable roofs, and pneumatic, revolving structures for modular buildings that were able to expand incrementally. At the same time, researchers continued to push cybernetic ideas in architectural directions. Eastman, for instance, envisioned spaces and users as feedback systems that would allow architecture to self-adjust to fit the needs of users.[3] Today, technological and conceptual advances in fields such as artificial intelligence, robotics, and materials science have enabled some of these early visionary ideas not only to be realised physically but also to be taken in important new directions. Kinetic architecture incorporating structural movement, and responsive or interactive architecture incorporating communication and real-time feedback between structure and user/environment have been materialised in recent innovative prototype projects from dECOi's Aegis Hypo-Surface to Hyperbody's Muscle Projects to ORAMBRA's Actuated Tensegrity Structure to Verschure's ADA Intelligent Space.[4]

The five papers that comprise this issue thus reflect a diversity of contemporary attitudes and responses to the challenges and potentials of digitally-driven architecture today and for the future. Through critical reflection, as well as built prototypes and projects, the authors of these papers interrogate the many dimensions of digitally-driven architecture. The issue opens with an 'introspective-retrospective' of the field by Michael Fox, a leading contributor to interactive design since the mid-1990s. Fox unfolds the history of interactive environments by taking us on a personal journey of the evolution of his own thinking and design practice in the area. The story he tells is a story of 'Catching Up with the Past'. The past here begins with cyberneticians Norbert Weiner and Gordon Pask and architects Cedric Price and John Frazer, who imagined machines and buildings as living, adaptable organisms in dynamic relationships with their environments. Fox's journey takes off from this heritage with a re-examination of kinetic - physically reconfigurable - architecture, and then progresses through a series of creative explorations that build incrementally on emerging technological ideas and innovations: automated kinetic systems with embedded, computational control devices; decentralised control systems; emergent, bottom-up control; modular, robotic control systems; biometic control processes; and finally, today, nanoscale bio-robotic control systems that drive all manner of physical and sensory adaptation at the level of materials. The overall trajectory is an advance towards the past - from a mechanical paradigm for interactivity to an organic, holistic one that begins to realise early cybernetic ambitions.

Fox's look back at interactive design is encapsulated in an elegant project by Daniel Rosenberg described in his paper 'Indeterminate Architecture: Scissor-Pair Transformable Structures'. Along the lines of Fox's advance to the past, Rosenberg aims to 'materialise and radicalise the seminal ideas' of pioneering cyberneticians and architectural theorists. He develops a novel, transformable (scissor-pair) structure that displays non-uniform, indeterminate mechanical behaviour. He then shows how this structure can be actuated in real time, and its form and behaviour 'radicalised', using recent AI techniques for robotics. The resulting digitally-controlled structure is able to 'sense', record, and learn from its own performance and interaction with users and the world, and adapt its behaviour accordingly.

Like Fox, Sokratis Yiannoudes takes a long view of kinetic and interactive design. However, Yiannoudes lays aside technological and functional considerations, and examines, instead, the historically-situated, socio-cultural drivers of this work. He argues compellingly that digitally-driven architecture is motivated by a long-standing, cultural, and perhaps psychological, need to comprehend and negotiate the boundaries between the animate and inanimate, between human and machine. Yiannoudes builds a novel conceptual framework for understanding digitally-driven architecture - often perceived as alive, social, emotional - based on Turkle's 'marginal object' concept viewing computers and computational objects as metaphorical and mechanistic and situated 'marginally' at the limits between living and non-living.[5]

Yiannoudes's framework is exemplified nicely in design projects described by MarkDavid Hosale and Chris Kievid in their paper 'Modulating Territories, Penetrating Boundaries'. They present an architectural installation, the InteractiveWall, with multi-sensory, real-time behaviours inspired by natural phenomena and triggered by internal and external stimuli. Sound, light, and movement combine to produce the semblance of a sentient, social being. The aesthetics and technologies behind the InteractiveWall were extrapolated in the Dynamic Sound Barrier - a real-world design proposal for an outdoor sound barrier that is activated and reveals itself in a landscape only in the presence of noise. Thinking beyond these projects, Hosale and Kievid raise important issues to do with current building and construction regulations that constrain architecture to static configurations. In this context, interactive architecture is seen as creating a demand to redefine architectural regulations and to engage architects in the design of new legislation for building.

Charlie Gullström expands the discourse and boundaries of digitally-driven architecture and rounds out this issue with a paper entitled 'Mediated Windows: The Use of Framing and Transparency in Designing for Presence'. Gullström uses a museum installation as the platform for a wider investigation into perceptual - as distinct from mechanical and physical - adaptation and interactivity. Her installation of digitally-'mediated windows' at a museum and a related outdoor site enables simultaneous, audio-visual extensions from one space to the other. Gullström addresses the historical relevance and implications of this form of interactivity - often missed in the discourse on contemporary technological applications - through a close examination of visually-extended architectural spaces in art and architecture. She explores the shift from the singular, window view and its historical depictions, to the digital, mediated window allowing for multiple views and modes of interaction.

While the theoretical issues raised by the papers in this issue help position digitally-driven architecture within a larger conceptual framework, the built prototypes and projects begin to demonstrate the potentials of digitally-driven architecture for the built environment and society at large. Following up on futurist visions of the 1960-70s and incorporating technological developments of the 1990s and later, digitally-driven architecture has broken with the modernist past on ideological, methodological, and typo-morphological levels. If top-down, programmatic function layout as well as standardised, serial-production determined typo-morphologically modernist buildings confined to static, modular, repetitive spatial configurations, then flexible, bottom-up, reconfigurable structures release built form from these confines. New responses to architecture's economic and ecological impacts (for example, with more efficient footprints) are now possible with the development of unprecedented concepts and their applications in digitally-driven architecture. Digitally-driven architecture accommodates human needs by addressing imperative requirements for flexibility and reconfiguration; equally important, it transcends pragmatic needs by instigating new evocative and 'emotive' relations with the built environment.

Notes

1. Archibots at UBICOMP 2009, Workshop group #4 <http://www.archibots.org/> [accessed 20 April 2010]
2. William Zuk and Roger H. Clark, *Kinetic Architecture* (New York: Van Nostrand Reinhold, 1970).
3. Charles Eastman, 'Adaptive-Conditional Architecture', in *Design Participation: Proceedings of the Design Research Society's Conference Manchester*, September 1971, ed. by Nigel Cross (London: Academy Editions, 1972), pp. 51–57.
4. ADA <http://ada.ini.uzh.ch/>, ORAMBRA - PROJECTS <http://www.orambra.com/>, HYPOSURFACE <http://www.hyposurface.org/>, HYPERBODY - MUSCLE PROJECTS www.protospace.bk.tudelft.nl/ [accessed 20 April 2010]
5. Sherry Turkle, *The Second Self: Computers and the Human Spirit* (Cambridge, MA: MIT Press, 2005).

Catching up with the Past: A Small Contribution to a Long History of Interactive Environments

Michael Fox

Introduction: introspection

I've been interested in interaction design in architecture for quite some time now; back to the time when I taught my first course in the late 1990s where the students used LEGO bricks for making little robotic architectural models. That was all we had back then; but the important point is - we did have something, finally, from the standpoint of tools that we could design with. In trying to understand why this journal issue in 2010 is dedicated to a subject matter that is really quite old historically, I speculate that the resurgence in this area has a lot to do with the current accessibility of the design and prototyping tools available to the profession of architecture. Only recently do architectural designers have tools that are both technologically and economically accessible for developing ideas in interactive architecture. We in architecture usurp what we can. Designing interactive architecture in particular is not inventing, but appreciating and marshalling the technology that exists, and extrapolating it to suit an architectural vision. Only recently do we see courses in interaction design and robotics being taught in schools of architecture all over the world whereas twenty years ago there were less than a handful. The illusion is that the field is fresh with new ideas illuminated by a wealth of built prototypes and real projects. While there are some genuinely new developments in terms of technology transfer in the areas of Interface Design, Autonomous Robotics, Biomimetics, etc. that will foster advanced thinking in the field, it is important to understand that the foundations have been around for quite some time. In writing this article, I have attempted to humbly step back and look at my own development in the area within the context of a much larger historical context. In retrospect, after nearly 15 years in the area, I did find the development to take a number of clear steps in a relatively logical progression. In summary, the journey began with kinetics as a means to facilitate adaptation. Work in this area led to integrating computation as a means of controlling the kinetics. The combination of these two areas led to the use of discrete mechanical assemblies as a systems approach to interaction design, which led to the thinking of control as bottom-up and emergent. Consequently I became fascinated with modular autonomous robotics and the notion that actual architectural space could be made of such systems. This in turn led to the exploration of biomimetics in terms of the processes, which eventually led to the idea that the parts in a system should get smaller to the point that they make up the matter itself. This leads us to where I am today, how I have evolved my thinking in interaction design over the years with students and my office. I am not sure where it goes from here - but at least it is interesting to explore.

Gordon Pask and cybernetics

I cannot really begin to describe my own development without a brief description of the historical context within which it lies. Essentially the theoretical work of a number of people working in cybernetics in the early 1960s laid most of the foundations in interactive architecture. At this time, Gordon Pask and other cyberneticians, including Norbert Weiner, made advancements toward understanding and identifying the field of interactive architecture by formulating their theories on the topic [fig. 1, 2]. Pask's 'Conversation Theory', served as the basis of much of the architectural development in interactive architecture at the time.[1] Essentially a model was developed in which architects interpreted spaces and users as complete feedback systems. Although recently Pask has been 'rediscovered' by the architectural community, he did fade away for quite some time. Pask's trouble was for the most part a lack of marketing potential in his physical proof-of-concept models. In general, it was also difficult for him and others at the time to get funding for anything that was not directly related to development of the digital computer including research in AI and cybernetics such as neural nets, evolutionary programming, biological computation, bionics, and so forth. Most research in these areas had to adapt to what could be implemented digitally in order to be funded.[2] Hence the work in these areas was not generally well funded, and therefore not prototyped, published, and disseminated. It did develop theoretically however in the late 1960s and early 70s by the likes of William Brody, Nicholas Negroponte, Charles Eastman, Andrew Rabeneck and others who expanded upon the earlier ideas explored in cybernetics by Pask and Weiner. Without going into any detail here, most of this theoretical work concerned interactive feedback systems related to adaptability.

Some early architects take interest

These early ideas rooted in cybernetics were picked up at the time by a few architects who solidly translated them into the arena of architecture. The main problem at this time however was that the computational means were not evolved to the extent that proliferation of concepts in cybernetics could take a strong foothold. In general it remained in the realm of 'paper architecture'. Cedric Price was perhaps the most influential of the early architects to adopt the early theoretical work in cybernetics and extend it to an architectural concept of 'anticipatory architecture' [fig. 3]. Many of his unbuilt projects influenced architecture of process that was indeterminate, flexible, and responsive to the changing needs of users and their times.[3] John Frazer extended Price's ideas, in positing that architecture should be a 'living, evolving thing' [fig. 4]. It's important to note that Price and Frazer both worked directly with Pask in developing their work over many years. John Frazer continued his work in the field for nearly thirty years with students at the Architectural Association in London[4] and other collaborators and summarised it in the book *An Evolutionary Architecture*, with an introduction by Pask himself. His work focused heavily on biological and scientific analogies and the sciences of cybernetics, complexity, and chaos. Although not in the same league as the others mentioned here, I worked for Fraser who subsequently became a strong influence in developing my own ideas.

Intelligent environments develop in parallel

While the architects were developing the ideas above based on cybernetics, it is important to also understand that there was another area being developed almost in parallel in digital computation and human interaction. In the late 1980s and 1990s, an explosion of development began to take place within the field of computer science. Out of this, fields such as 'intelligent environments' (IE) were formed to study spaces with embedded computation and communication technologies, creating spaces that bring computation into the physical world. Intelligent environments are defined as spaces in which computation is seamlessly used to enhance ordinary activity. A lot of technologies were developed in this area which dealt with sensing and human behaviours, but the architecture was always secondary as developed under the mantra of 'seamlessly embedded computation'.[5] In other words there was very little architectural involvement in a very exciting area that was developing computationally-enhanced environments. These developments were essentially fuelled by the concept of 'ubiquitous computing'

Fig. 1

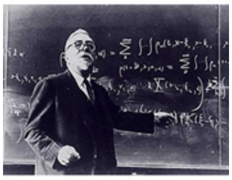

Fig. 2

Fig. 3

Fig. 4

Fig. 1: Gordon Pask

Fig. 2: Norbert Weiner

Fig. 3: Cedric Price

Fig. 4: John Frazer

which was originally defined as a general concept for computation which is thoroughly integrated into everyday objects and activities, and sits at the intersection of computer science, behavioural sciences, and design.[6]

Corporate interests also develop in parallel

Corporate interests also developed market-driven roles which began in the late 1950s and were extremely important as they directly involved the users out in the real world; however they were not integrated with the earlier theoretical architectural concepts of interactivity. These cultural and corporate interests played major roles in influencing computationally-enhanced environments through the development of numerous market-driven products and systems that directly involved users in the real world. Computationally-driven environmental control systems were developed within buildings as a direct derivative of the introduction of sensors with remote signalling allowing for a central control room.[7] The invention of the 'remote control' also came along at this time, enabling the user to assume a larger role as an operator of objects in space. In the 1970s energy management systems were introduced as well as microprocessors but, for the most part, the architecture world had yet to embrace the promises of such technologies from an interactive standpoint. In the 1980s, the PC became the interface that replaced the central console control, distributed direct digital control replaced conventional control systems, and communication could be programmed to take place on local area networks.

Eventually architects usurp enough to make something

In the 1990s everywhere you turned there was a 'smart home' and 'smart workplace' project being initiated that relished the newly available technological advancements. It was a time when wireless networks, embedded computation, and sensor effectors became both technologically and economically feasible to implement. This feasibility fuelled experimentation with many of the ideas of the early visionary architects and theoreticians outlined above that had been stifled by the technological and economic hurdles of their day. It was at this time that the economics of obtaining cheap computational hardware and increased aptitude to integrate computational intelligence into architecture began to be reinvestigated by architects. The interactive architecture workshop at the Bartlett School of Architecture was initiated in the early 1990s as a pioneering forum for actual architectural pursuits under the guidance of Stephen Gage. Also, the use of the Internet undoubtedly played a major role in both the technological and intellectual dissemination responsible for progress in the field. Since the 1990s, numerous architecture schools have expanded their programs to incorporate interactive design.

My work begins with kinetics as a means to facilitate adaptation…

So it was then in line with the long context outlined above essentially where my work began. I began to re-examine the long history of kinetics in architecture under the premise that performance could be optimised if it could use this newfound computational information and processing to physically adapt.[8] In retrospect I developed an interest in interactive architecture in somewhat of an opposite way than one might expect today. I founded a research group at MIT that was focused on kinetic solutions in architecture and how such systems can facilitate adaptability. After exploring numerous kinetic projects with this focus on adaptability, such as the Abbot Fence [fig. 5] and the Auto Lift [fig. 6], it became an obvious next step that such spaces and objects should be coupled with some sort of digital sensing and actuation that can allow them to reconfigure themselves. I say I came about this topic in a roundabout way because today, when we have these 'smart' environments everywhere, the obvious route would be to say that we have this space that is really smart; that understands the environment

Fig. 5

Fig. 6

Fig. 5: Abbot Fence, Mechanical kinetics - Project by Foxlin.

Fig. 6: Auto Lift, Mechanical kinetics - Project by Michael Fox and RoArt.

inside and outside and understands various data about the users including behavioural patterns, but what is it doing? What is it, or can it, physically do in an architectural way to adapt? I was also very interested in the premise that performance could be optimised if it could use computational information and processing to control physical adaptation in new ways to respond to contemporary culture.

…which led to integrating computation as a means of controlling the kinetics

Relative to the time kinetics has been around in architecture, embedded computation (EC) is in a state of relative infancy. EC can be reduced to possessing a combination of both sensors (information gatherers) and processors (computational logic to interpret). EC is important not only in sensing change in the environment, but also in controlling the response to this change. The combination of embedded computation and kinetics is necessary to allow an environment to have the ability to reconfigure itself and automate physical change to respond, react, adapt, and be interactive. Advancements in the technology involved with hardware has begun to free computation from our existing notions of what computers are, and allow computers and the way we use them to evolve as they become embedded into the physical fabric of our everyday surroundings. In the future, computers will become intrinsically integrated into our lives to the extent that we will design objects, systems, and our architectural environments around the capabilities of embedded computation, and not the other way around.

With this in mind, I began to develop a number of projects dealing with both pragmatic and humanistic needs. Many of these projects, such as the iSpa [fig. 7] and the iZoo [fig. 8], were full-scale interactive environments developed by students at various universities. Within these environments, each system in a space is responding not only to the people in the space but also to the behaviours of the other systems. These individual systems can have both the fundamental logic and hardware to allow them to be extremely good at executing the specific tasks they were intended to do while simultaneously networking into a collective whole that can be controlled by an overarching logic.

…which led to thinking of systems as discrete mechanical assemblies

Extending the notion of thinking of a room then as a collective whole with different specific task systems, the idea was that each system itself became an assembly as well. Rather than a single skylight with a limited range of capabilities, the skylight could itself become an assembly with a far greater range of inherent capabilities. I developed numerous projects with students at this time exploring such systems of control including the Ex-Com Cubes project [fig. 9] and the large human scaled Flock-Wall exhibit [fig. 10]. The important point is that each individual actuating device is then controlled by a decentralised controller at a local level. This model of decentralised identification and control is based on neural networks and simplifies the implementation of the control algorithm. Decentralisation is valuable on a number of points. In creating many self-similar parts, there is a redundancy in terms of control, an economic savings in terms of mass-production and an increased robustness to failure, in that if any single part fails, the system as a whole does not fail. When there are many unknown stimuli, such as groups of individuals behaving in unknown ways and an exterior environment which is constantly changing, then decentralised intelligence can be a very effective way to handle the sensing and response (perception and action).

…which led to the thinking of control as bottom-up and emergent

I began then to develop a number of projects based on decentralisation which forced a new outlook on how the control of these systems should be dealt with. It was also important that these projects, including the Bubbles [fig. 11] and Neural Sky [fig.


Fig. 7


Fig. 8

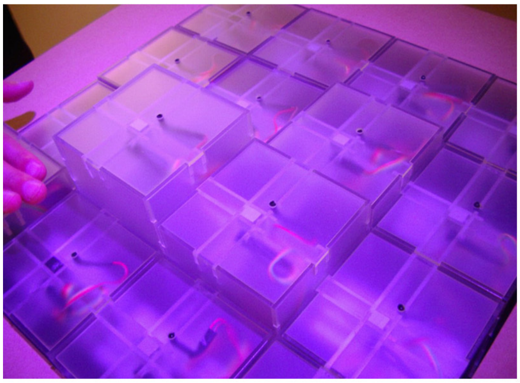
Fig. 9

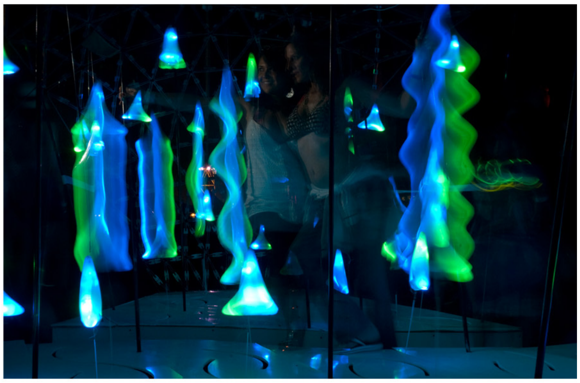
Fig.10

Fig. 7: iSpa - Interactive Environment Developed in Architectural Robotics Course at Art Center College of Design

Fig. 8: iZoo - Interactive Environment Developed in Architectural Robotics Course at SCI-ARC

Fig. 9: Ex-Com Cubes - Interactive Exhibit Developed in Architectural Robotics Course at Hong Kong Poly U.

Fig. 10: FlockWall - Interactive Environment Developed in Architectural Robotics Course at Cal Poly Pomona

12], were large enough to understand real human interactions and that they were up long enough to understand emergent behaviours. Most architectural applications are neither self-organising nor do they have higher-level intelligence functions of heuristic and symbolic decision-making abilities. Most applications do, however, exhibit a behaviour based on low-level intelligence functions of automatic response and communication. When a large architectural element is responding to a single factor then a centralised system can be effective in executing a command to a single agent, but when there are many unknown stimuli, or many small autonomous parts, then decentralised intelligence is the most effective way to handle the sensing and response. The more decentralised a system is, the more it relies on lateral relationships, and the less it can rely on overall commands. In a decentralised system there is normally no centralised control structure dictating how individual parts of a system should behave, local interactions between discrete systems therefore often lead to the emergence of global behaviour. The idea of behaviour that emerges became very interesting to me and I began to explore this idea in very simple ways through a number of projects. An emergent behaviour can occur when a number of simple systems operate in an environment that forms more complex behaviours as a collective. The rules of response can be very simple and the rules for interaction between each system can be equally simple, but the combination can produce interactions that become emergent and very difficult to predict.

…which led to the idea that architectural space itself could be made of robotic systems

I began moving away from developing traditional uses of automated mechanical devices in architecture to looking at the potential of transformable systems that are made up of a number of small robots. I taught numerous design studios in which students developed modular autonomous robotic modules [fig. 13, 14] that served as the base building blocks for architectural explorations. Manufacturing technologies compounded with recent advancements in software (computational intelligence) allow the robotic parts in these systems to be increasingly smaller and smarter. Current manufacturing technologies have allowed microprocessors to grow increasingly smaller, cheaper, and more powerful and we are seeing that we now have the potential to think of space itself as being organised in a computational network. For many applications ranging from cleaning carpets and windows to adjustable furniture, we are seeing a distancing from the precedent of figural humanoid robots to transformable discrete systems. Current advancements in self-assembling robots, specifically dealing with the scale of the building block and the amount of intelligent responsiveness that can be embedded in such modules, are setting new standards for robotics. These new standards are extremely exciting in light of the role of autocatalytic processes, defined here as a reaction product itself being the catalyst for its own reaction. In the context of modular reconfigurable robotics such processes describe how the pace of technological change is accelerating because of these processes. In other words, the process is ‘autocatalytic’ in that smart, articulate machines are helping to build even smarter, more articulate ones. The potential is that in the near future, modular reconfigurable space could hugely impact the way people live in space, and the relationships between users and the space itself. Then if it is possible to build space out of parts that have the ability to reconfigure themselves, it is really up to architects and designers to design how these pieces will come together and how these configurations will respond to the constant flow of information between inhabitant and space. So then in light of the potential of autocatalytic processes, robotics in architecture is not at the beginning, nor is it by any means at an end; but it is, in a sense, at the end of the beginning.

Fig. 11

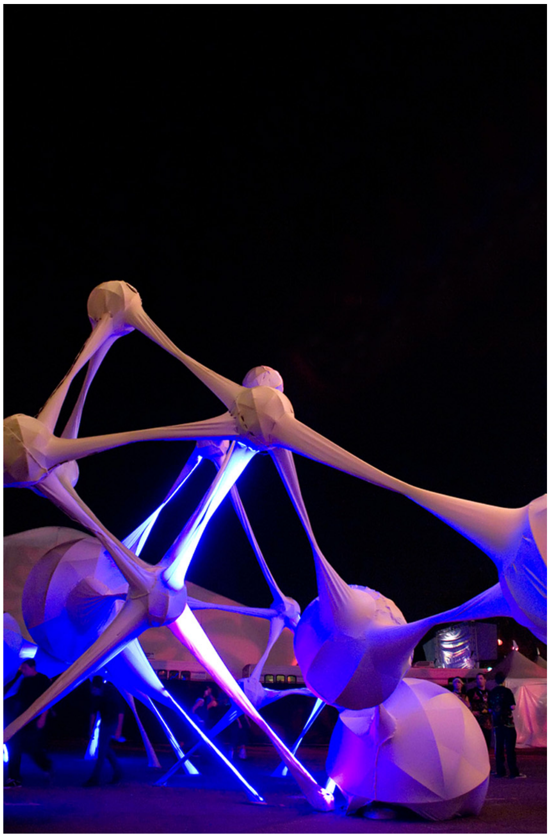

Fig. 12

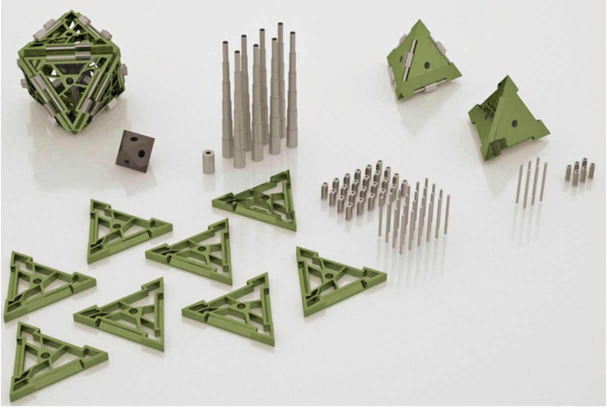

Fig. 13

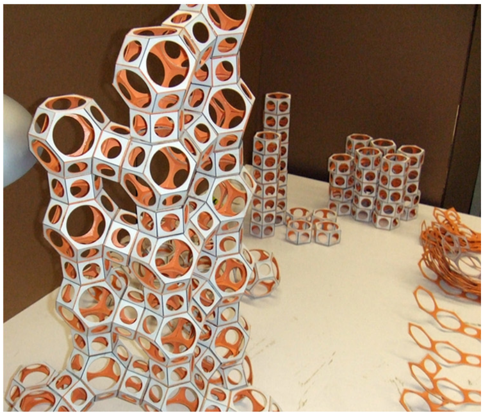

Fig. 14

Fig. 11: Bubbles, Interactive Environment - Project of Foxlin

Fig. 12: Neural Sky - Interactive Environment Developed in Architectural Robotics Course at Cal Poly Pomona

Fig. 13: Modular Autonomous Robotic Module Components - Student project at Cal Poly Pomona

Fig. 14: Modular Autonomous Robotic Module Components - Student project at SCI-Arc

…which led to the exploration of biomimetics in terms of processes

I became fascinated at this point by modular autonomous robotics that had the potential to reproduce themselves. New available technologies like the fab@home 3-D printer, which has the capacity to print with a wide palette of materials, and mobile CNC routing robots became the inspiration for what might be possible architecturally with modular robotics. With the possibilities of such new CNC processes, I directed several studios under this premise of what I call 'redesigning the brick'. The heuristic approach is very bottom-up, in that you first design the brick (robotic module) and then the architectural possibilities are very much influenced by the inherent possibilities and limitations of that particular module. These modules began with nature as an inspiration for how they could adapt [fig. 15, 16].

Consequently this approach led directly to an exploration into biomimetics. I was interested in architectural systems that could operate like an organism, directly analogous with the underlying design process of nature. Architectural robotics utilised at such a level could allow buildings to become adaptive much more holistically and naturally on a number of levels. Biomimetics studies systems, processes, and models in nature, and then imitates them to solve human problems. It lies at the intersection of design, biology, and computation. Put simply, nature is the largest laboratory that ever existed and ever will.

Understanding the processes by which organisms grow, develop and reproduce then became an invaluable precedent for how such small mechanisms in an architectural environment could potentially operate. This area of study is called developmental biology and includes growth, differentiation, and morphogenesis. In terms of adaptation, the area of morphogenesis, which is concerned with the processes that control the organised spatial distribution of cells, is particularly relevant.

The important thing here is that such systems reposition the role of the designer. As Gordon Pask states in his foreword to the book *An Evolutionary Architecture*: 'The role of the architect here, I think, is not so much to design a building or city as to catalyze them: to act that they may evolve.'[9] While such ideas have been around for quite some time in the architectural world in terms of scripting, generative design etc., biomimetic possibilities seem very different as they have the potential to affect the architecture itself after it is built. I am not saying that we are going to see buildings made of computational sand anytime soon but it has become hard-science fiction and therefore quite easy to speculate fascinating potential futures based on extrapolating existing technologies.

…which led to the idea that the parts in a system should get smaller to the point that they make up the matter itself

It seems we are nearing the end of large-scale architectural robotics before we ever got a chance to really know it. Just at the time when we are starting to see many built projects come to fruition, it seems that any application of mechanised robotics in architecture is starting to seem very quickly outdated. The notion of an embedded mechanical shading device seems absurd no matter how intelligent the system is, when the glass itself can change its visible transmittance, reflectance, or UV resistance. The idea of small robots scaling a building to repair a facade or clean the glass seems equally absurd when the materials can heal themselves from decay and cracking like a bone remodels itself and the windows can utilise an internal strategy such as creating ultrasonic vibrations to clean themselves. A mechanical device to scrape snow from a roof could be replaced by a material that heats itself and never allows snow to collect in the first place. Not long ago a futuristic paradigm for interac-

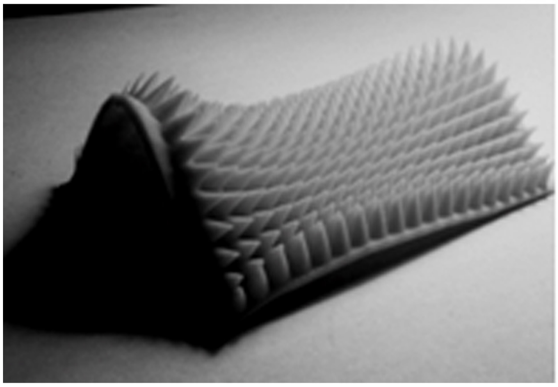
Fig. 15

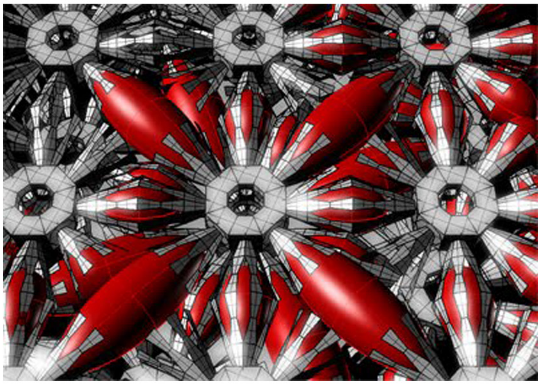
Fig. 16


Fig. 17

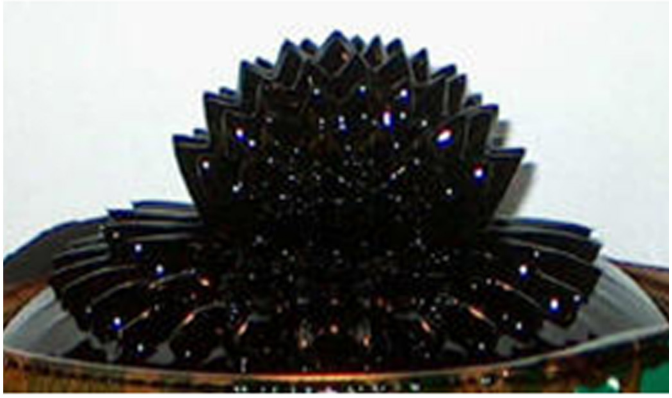
Fig. 18

Fig. 15: Biomimetic Module - Student project at Cal Poly Pomona
Fig. 16: Biomimetic Module - Student project at Cal Poly Pomona
Fig. 17: HelioDisplay, Interactive 3-D display system - Developed by Foxlin
Fig. 18: Nanocity Exhibit, Robotically controlled interactive forms in ferrofluid - Project of Foxlin

tive architecture seemed visionary if the whole of a building had kinetic potential and was computationally controlled and networked to adapt to any architectural scenario. The problem with this vision today is one of scale: it is focused on a building as a composition of discrete systems or devices rather than on the potentials of the materials that compose the building. My office was fortunate to develop several projects that served as inspiration for the scale of robotics in architecture such as the Helio-Display interactive 3-D display system [fig. 17] and the Nanocity project [fig. 18].

We must change our general preconceptions of robotics with respect to scale to understand the potentially profound role in architecture. To illustrate, let's use the example of a smart kitchen with an 'intelligent' mechanical countertop which can raise and lower itself when needed and a smart cabinet above which can assist you in retrieving food items as desired. Both the countertop and the cabinet understand the actions of each other and while only one may deduce a response based on environmental sensing, the other may operate accordingly based on the actions of the other device. For example, as the countertop senses the height of an individual it may lower itself to accommodate a specific food preparation need, and the cabinet will use the information of the countertops' action and lower itself and organise the food items accordingly to a learned pattern of behaviour of what the person typically eats at a specific time of day. The above scenario, while perhaps not commonplace, is very realistic and achievable by today's technological means. Let's expand the scenario further now by imagining that both the countertop and the cabinetry are not mechanically-driven 'devices' but are rather composed of thousands of smaller mechanical modules (the size of dice) which make up the devices themselves. The distributed sensing and control would now happen not at the level of the countertop and the cabinetry but at the level of each of the tiny modules. The geometrical flexibility, sensing capabilities and robustness of each of the larger 'devices' would then be greatly enhanced. Let us then extend the example above once again whereby the countertop and the cabinet are not composed of small modules but are composed of bionanotechnological materials which can morph their shapes to adapt at a very high degree of resolution. The materials are not veneers to traditional devices but are the fabric of the devices themselves with sensing and control operating biomimetically at a very small scale. At this level the countertop and cabinet can control additional attributes such as temperature, texture, colour, opacity, etc., and potentially then large-scale kinetics as well. Large-scale kinetics can and will also still be possible but they will actuate much more holistically which takes a bit of a change in mindset to conceptualise. An example might be that rather than a cabinet door opening by a traditional computer-controlled linear actuator rotating the static door on hinges, the door would essentially be one with the wall and all along the seam of rotation would be thousands of very small hinges which could be actuated by means of hydraulics much like the stem of a plant. The point is to think of modular autonomous robotics scaled down to the point of becoming the material itself. Several transformational materials have already been developed which demonstrate exciting potential, particularly in the area of fabrics and polymers. A new robot developed by 'iRobot' for instance, can change its shape and squeeze into tight places using a concept called 'jamming skin-enabled locomotion'. The potential attributes of kinetics working at such a very small scale can extend beyond strictly facilitating needs, to simultaneously engage a wide range of human sensory perceptions. These new interactive assembly systems will bring new unprecedented levels of customisation and reconfigurability to the architectural palette

Such an extrapolation of advancements in both robotics and new materials demonstrates an architectural future whereby adaptation becomes much more holistic and operates on a very small internal scale.

Conclusion

In conclusion, technical advancements in manufacturing, fabrication and computational control will continue to expand the parameters of what is possible in robotics, and consequently influence the scale by which we understand and construct our environments. This scaling down is beginning to force a reinterpretation of the mechanical paradigm of adaptation. The future of interactive environments will most certainly involve re-examining the scale by which things operate to the extent that much of the operations happen within the materials themselves. In many cases traditional mechanical applications seem to be approaching the beginning of the end. Ironically, I came about these conclusions with a foundation in strictly mechanical typologies. While I believe that there is a great aesthetic honesty and dynamic appeal to mechanised kinetics in architecture, the potential benefits of a biological paradigm seem to outweigh those of the traditional mechanical paradigm. It is also important to remember that I am not advocating the end of mechanics, but simply a reinterpretation of the scale of the mechanics. Mechanics then are interpreted more literally as biologic rather than mechanical in the sense of a machine.

I am very excited to witness the explosion of interest in interactive architectural environments, but caution that such should be pursued with an understanding of the inclusive historical context which laid the foundations in this area quite some time ago. Designing such environments is not inventing after all, but appreciating and marshalling the technology that exists at any given time, and extrapolating it to suit an architectural vision. As we continue to expand the possibilities of what is possible today with the accessibility of new tools we can begin to catch up with the past.

Acknowledgements

I would like to thank the many students at Cal Poly Pomona, Sci-ARC, Hong Kong PolyU, Art Center College of Design and MIT who have worked to develop many of the projects and ideas mentioned in this text. I would also like to thank several expert collaborators who have regularly contributed to the development of these ideas, including Scott Howe from NASA/JPL and Ed McCullough from Boeing and Darius Miller.

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Biography

Michael Fox is the founder and a principal of Fox Lin Inc. in Los Angeles, California. In 1998, Fox founded the Kinetic Design Group at MIT as a sponsored research group to investigate interactive architecture. Fox directed the group for three years. His practice, teaching and research are centred on interactive architecture. He is an associate professor at Cal Poly Pomona and has taught previously at MIT, The Hong Polytechnic University, Art Center College of Design and SCI-Arc in Los Angeles. Michael Fox is the author of the book *Interactive Architecture* published by Princeton Architectural Press.

Indeterminate Architecture: Scissor-Pair Transformable Structures

Daniel Rosenberg

Introduction

Most traditional architectural theories and practices aim at designing unique, fixed and ideal solutions. The general belief is that the final shape of a building can be achieved by analysing present situations, such as clients' stated needs, demands and desires. Likewise, this approach is based on descriptions and assumptions, which consider future situations as certain, invariable and in a particular moment in time. However, are the situations of the present representative of a reality to be produced in the future, during the life of the building? And, moreover, are these situations fixed and invariable throughout time?

The vision here is that during the design process, future situations are uncertain, since not only buildings generate unprecedented and unexpected situations, but also these situations evolve and change through use and time. This paper addresses this problem through proposing an indeterminate architecture, wherein the building remains in an open-ended process of definition and redefinition according to clients' incidental needs, demands and desires. This vision is defined by two complementary design considerations: Designing the Range and Enabling the Choice. While Designing the Range refers to transformable buildings able to offer a variety of states, Enabling the Choice refers to the users' selection of states, within the range and according to emergent situations.[1]

This paper is aligned with some seminal ideas proposed in the sixties and seventies, which promote the design of a range to enable the choice through an indeterminate architecture sympathetic to uncertainty, incompleteness and emergent situations. More specifically, this paper attempts to materialise the intriguing and utopian architecture envisioned by the Archigram movement in the sixties,[2] and, likewise, aims at radicalising the inventive and technical kinetic architecture proposed by William Zuk and Roger H. Clark in the seventies.[3]

It is important to clarify that, even though it is possible to associate this research with contemporary explorations of adaptable, interactive and performative architectures,[4] the strategy here is to refresh the current discourse and contribute by merging old ideas with theories and technologies of today. The objective is to materialise and radicalise the seminal ideas about indeterminate architecture by relating the engineering knowledge on scissor-pair transformable structures with the Artificial Intelligence (AI) theories and techniques on robotic control within uncertain environments. While scissor-pair transformable structures materialise indeterminacy through mechanical and physical shape variation, robotic control radicalises indeterminacy by enabling the modification of the structure's behaviour in real-time.

The structure of this paper is organised around two sections, the two directions for the design of indeterminate buildings: Designing the Range and

Enabling the Choice. Both sections present, first, an architectural background to give initial definitions and directions, second, a technical approach to extend the scope of current indeterminate solutions, and, third, an empirical experiment to propose some novel architectural applications. The first section, Designing the Range, addresses the uncertainties about the future use of the building through the design of a range of alternatives instead of a unique, fixed and ideal solution. While Archigram's ideas are presented to show how indeterminacy can be pushed to an extreme by proposing flexible and almost immaterial building environments, kinetic architecture is used to address the technical domain of indeterminacy by mechanical structures able to transform according to variable demands. This theoretical background is then related to the analysis of scissor-pair transformable structures, wherein existing engineering solutions are studied in order to find novel shapes and behaviours. Finally, a novel type of scissor-pair solution, able to transform in a non-uniform manner,[5] is proposed along with a digital and physical prototype to show some architectural applications.

The second section, Enabling the Choice, focuses on how the range of alternatives extends the design process to the real-world through the continuous shape definition and redefinition according to users' demands. While Archigram illustrates how buildings could be designed as machines that interface between the environment and the user, kinetic architecture shows the advantages and limitations of actuated mechanisms. Artificial Intelligence (AI) theories and techniques are then presented to show how to design indeterminate solutions: by engineering machines that interface directly with the real-world, self-sense, record and learn from their own physical performance. These AI techniques are, finally, incorporated into the novel scissor-pair solution using sensory-motor actuation, to radicalise indeterminacy by facilitating the modification of the building-machine's behaviour in real-time.

A final section provides a reflection about the work's weaknesses and strengths, and some future lines of research within the design of indeterminate buildings and scissor-pair transformable structures.

Designing the Range

Range of alternatives

Assuming the uncertainties about the future use of a building implies a different notion of the design process. Instead of the architect's attempt to find a unique, fixed and ideal solution, the challenge is designing an indeterminate solution, offering a range of alternatives for the users of a building. In order to design an indeterminate architecture, the designer has to envision a range of possibilities, leaving part of the definition open, according to incidental situations that may occur in time and throughout the use of the building.

Archigram acknowledges that a building should express 'its habitants' supposed desire for continuous change'.[6] Therefore, they envision an indeterminate architecture in an open-ended process of shape definition, wherein the architect has to design the system or technical apparatus that would enable the choice of a solution out of a number of alternatives.[7] According to this view, the design process is reoriented towards the definition of flexible systems: buildings able to transform themselves to offer a range of alternatives instead of unique fixed and inflexible solutions. For Archigram, indeterminacy is materialised in that way, by designing almost immaterial, formless and purposeless building environments.

One of Archigram's most radical projects in relation to indeterminacy corresponds to The Thing, designed by David Greene and Michael Webb in the context of the Living City installation in London 1963. Instead of designing a traditional building Greene and Webb proposed a placeless triangulated structure floating 'with an unstated purpose, hopefully benign, arriving in a bleak landscape'.[8] Here, the

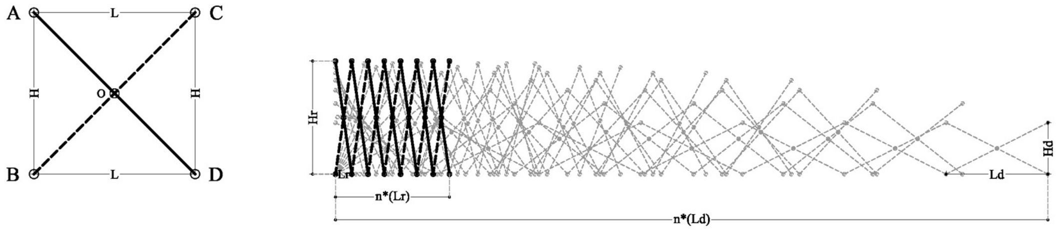

Fig. 1

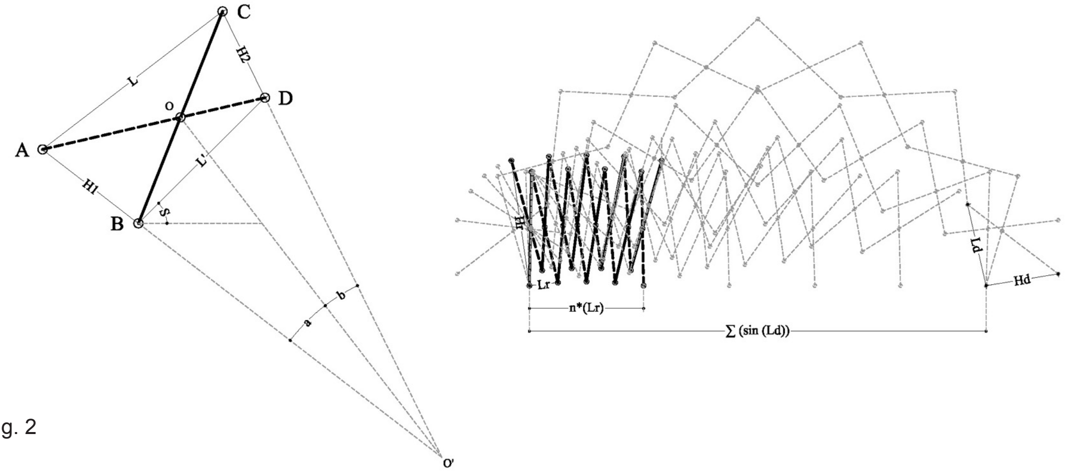

Fig. 2

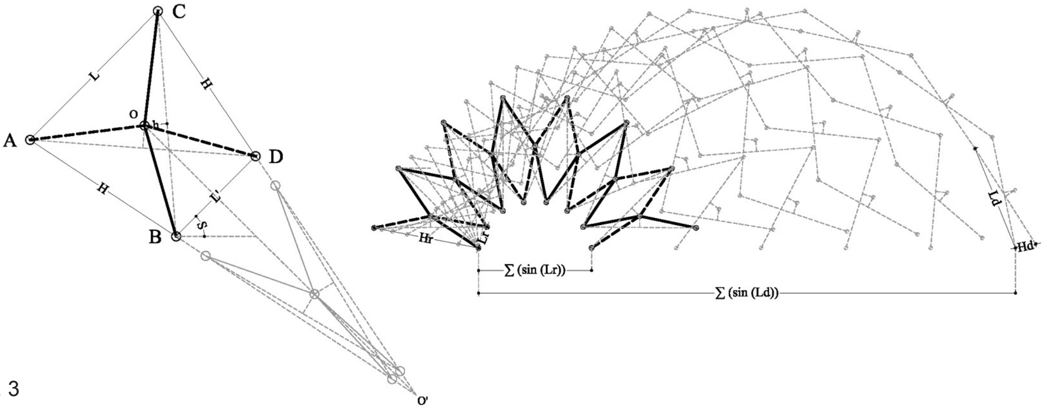

Fig. 3

Fig. 1: Centre scissor-pair solution.

Fig. 2: Off-centre scissor-pair solution.

Fig. 3: Angulated scissor-pair solution.

shape and physical boundaries of the building are dissolved, pushing indeterminacy to an extreme, wherein the range of alternatives is so broad and open that the building almost disappears. Moreover, The Thing not only responds passively to uncertain situations but rather its radical indeterminacy is an active agent that creates and fosters an even more ambiguous and emergent reality.

Following the utopian lines of the Archigram movement, Zuk and Clark propose a more technical approach to indeterminacy by introducing the concept of kinetic architecture. They show how the Archigram approach to indeterminacy could be materialised through transformable buildings, able to change their shape in order to meet different functions. According to them, the impossibility of foreseeing future changes would lead to the incompleteness of the design process and its extension into the realm of physical kinetic buildings. They argue that, since the design process is incomplete and the form can be kinetically changed, the initial built form does not have to be correct and that, instead, the designer may offer a range of possible states: 'The architect/designer will provide a range of forms capable of meeting a range of pressure changes.'[9]

This range of alternatives, in the case of kinetic architecture, corresponds to the transformation and multiple states that a system is able to produce according to the movement and rearrangement of its internal components. However, according to Zuk and Clark this approach to indeterminacy implies the prediction of the range of possible changes that may occur in the future. Likewise, the form can only 'respond to a range of functional changes possible within the initial envelop limitations'.[10] Even though kinetic architecture offers a more technical and possible approach to indeterminacy, it also restricts the freedom and reduces the radicalism of the utopian and playful ideas proposed by Archigram. The kinetic idea offers a limited approach to indeterminacy. It is necessary to know the range of possible situations beforehand, to design systems that have predetermined possible states. Therefore, the challenge, at this stage, is to design a range as broad, open and flexible as possible, studying the in-between states and analysing the different shapes that are produced. It is about probability: the more variety of the system, the more the chances to meet the change of pressures.

Scissor-pair transformable structures

Kinematics is the field that studies the geometry and motion of mechanical systems.[11] In a mechanism, the different components move relative to each other according to the geometry and the degrees of freedom of the system. Scissor-pair transformable structures are mechanisms that have one degree of freedom, which enables the internal propagation of movement, from one component to another. These mechanisms are able to transform as they follow a sequence of states, changing physically from one overall shape to another in a continuous process, offering us the chance to design and build indeterminate physical solutions. Even though their transformation capabilities have been used in engineering design to create and optimise collapsible structures, they have great potential if considering the in-between states, the range of possible shapes, between retracted and deployed positions.

A simple scissor-pair transformable structure can be made from a pair of straight and rigid bars connected in the middle with a pivot or scissor hinge. This initial component is called *scissor-pair* and it defines a single-degree-of-freedom mechanism.[12] Through the assembly of these scissor-pair components it is possible to create two- and three-dimensional scissor-pair transformable structures. The single-degree-of-freedom property enables the control of the transformation process through the propagation of rotations from one scissor-pair to the next one and vice versa. In other words, because all scissor-pair components are linked, the rotation

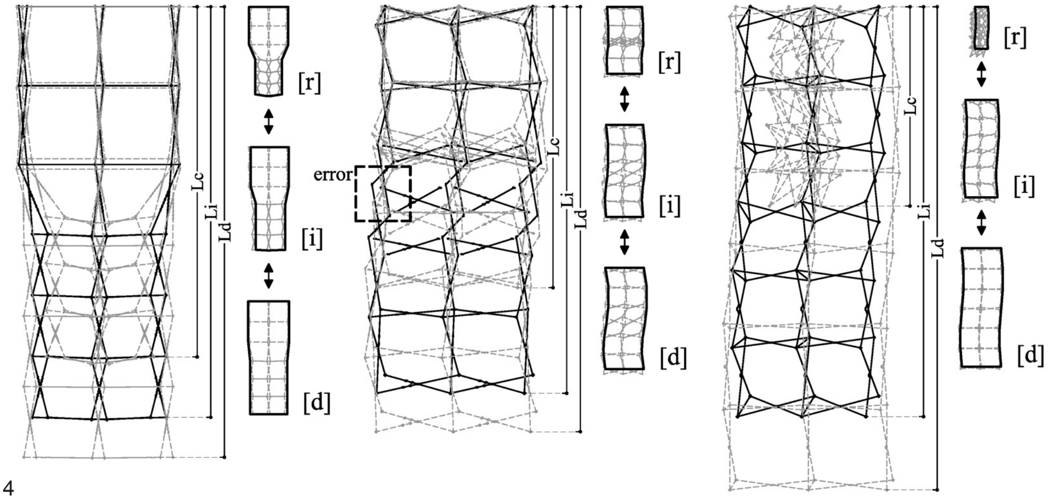

Fig. 4

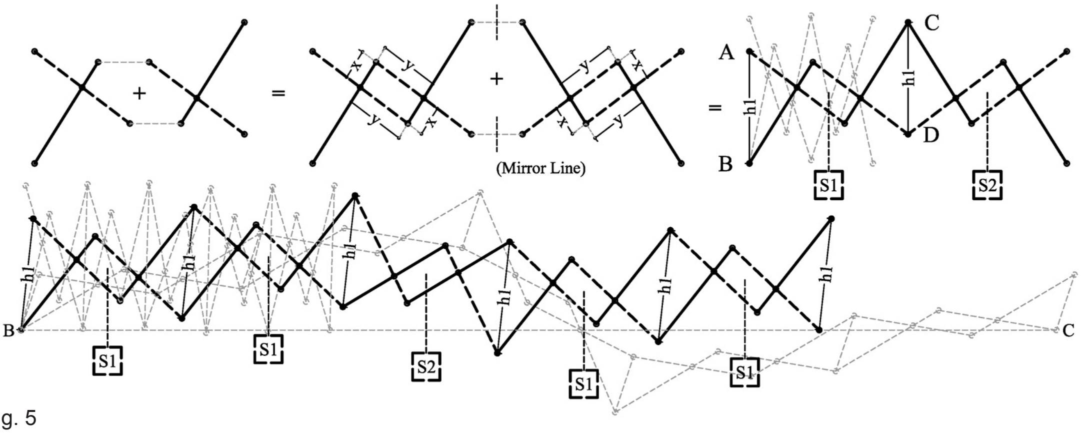

Fig. 5

Fig. 4: From left to right: Three-dimensional assembly of centre, off-centre and angulated solutions.

Fig. 5: Double scissor-pair component: proportions and two-dimensional array.

of one local assembly will affect the behaviour of the entire structure. This principle of propagation is essential because it reduces the actuation and control mechanism to one variable, the rotation of only one component. It also determines the synchronised and smooth transformation between states.[13]

These types of structures have been generally used for rapidly assembled constructive systems which are able to transform their shape between two extreme states: from a compact and retracted state to an extended and fully deployed one. Some applications have been proposed in movable theatre structures,[14] expandable space structures,[15] collapsible portable shelters,[16] deployable domes,[17] and retractable roof structures.[18] In all these applications the main objective has been to optimise the ratio of extended and contracted length and to find advantageous structural configurations.

The structural engineering literature covers a reasonable understanding of the shapes and behaviours that can be designed and built using the single-degree-of-freedom property as a constraint. There are mainly three general approaches to the problem according to the shape of the rigid bars and the position of the scissor hinge: the centre scissor-pair, the basic and traditional configuration used by Edwards and Luckey,[19] the off-centre scissor-pair, pioneered by Pinero, Zeigler and Escrig,[20] and the angulated scissor-pair, discovered by Hoberman and further developed by You and Pellegrino.[21]

Figures 1, 2 and 3 show the different types of scissor-pair transformable structures and the shapes and behaviours they produce in the in-between states, between retracted and deployed states.[22] However, the intention, here, is neither the optimisation of collapsibility nor the structural performance of the systems, but rather the flexibility of the range, the variety of shapes the systems are able to produce. By analysing the different shapes within the range of the transformations, it is possible to note that the off-centre solution is the only one that behaves in a non-uniform manner, generating a continuous transformation from planar to curved profile while deploying [fig. 2]. The centre and the angulated solutions behave uniformly and, thus, the overall shape during transformation remains constant. Particularly, the angulated solution offers great advantage since it enables the creation of transformable curved profiles. In-between configurations, however, are only scaled versions of each other and, therefore, the transformation of these types of solutions does not offer a variety of shapes.

As shown in figure 4, while the uniform behaviour of the centre and angulated solutions enable three-dimensional assembly, the off-centre solution generates an error. The unique off-centre property of non-uniform behaviour during transformation - wherein the in-between states correspond to different shapes - disallows the possibility of three-dimensional assembly. This can be explained by analysing how the two lines A-B and C-D, and their projection towards the intersecting point O, change their angle during transformation (see figures 1, 2, and 3). Within centre and angulated structures the transformation follows these control lines, which are fixed, whereas in the off-centre solution they change throughout transformation, disallowing three-dimensional assembly.

Even though centre, off-centre and angulated solutions have provided a valuable contribution to the design of transformable structures, the repertoire of possible applications is still limited to a small number of shapes and behaviours. These transformable structures have been designed through an engineering and analytical approach that aims at optimising collapsibility and structural performance without considering the in-between states as an opportunity to generate a range of variable shapes. Nevertheless, these solutions correspond to a starting point for the development of a novel solution,

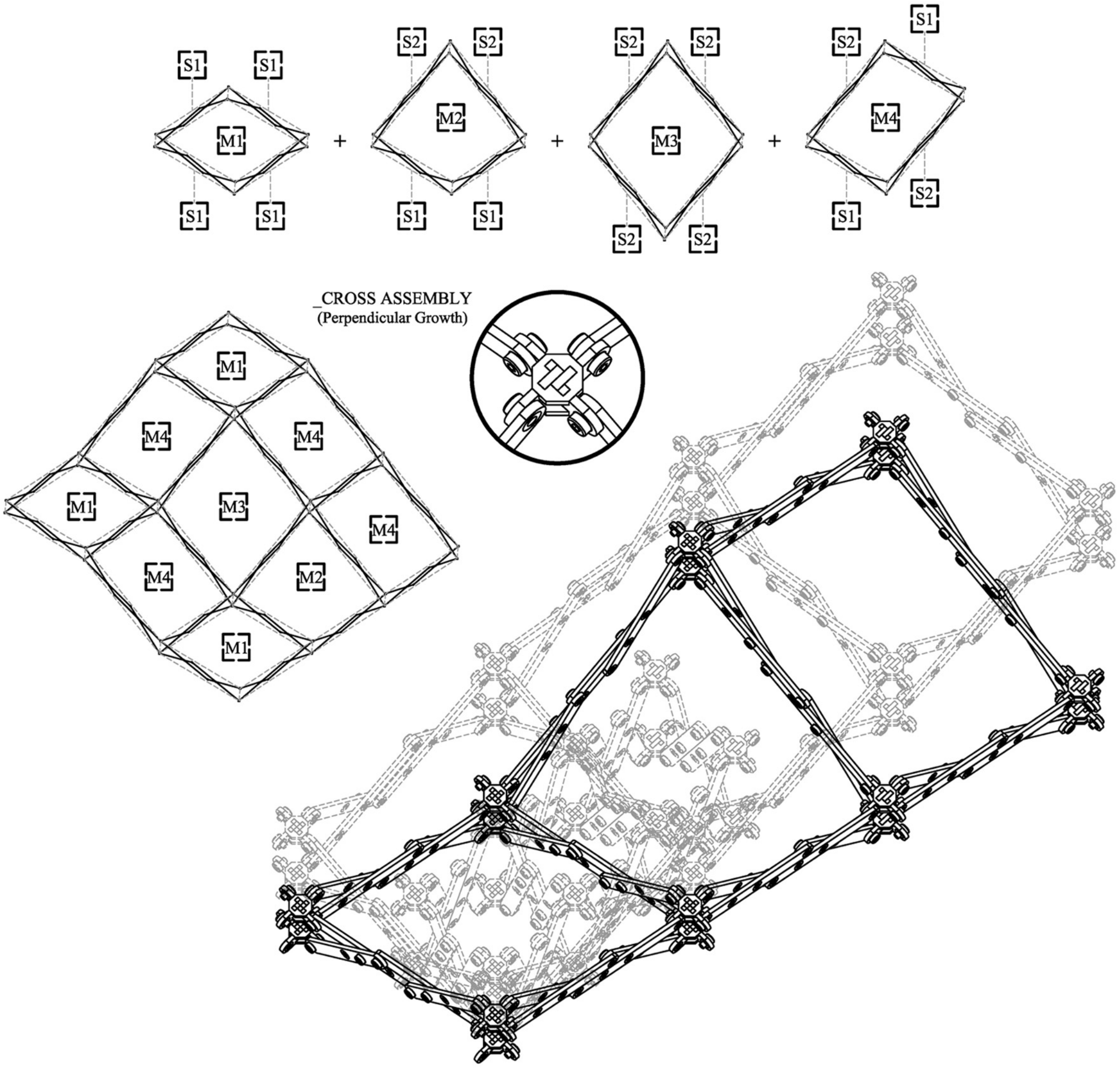

Fig. 6: Double scissor-pair three-dimensional array.

able to combine their properties and advantages: on the one hand, the three-dimensional capabilities of the centre and angulated solutions, and, on the other hand, the non-uniform transformation of the off-centre solution, controlled by single actuation: a transformable structure able to offer a range of variable shapes, a range of alternatives, aiming at the construction of physical indeterminate solutions.

Experiment 01: Non-uniform transformations

It is possible to combine two off-centre scissor-pair components in a novel manner to create a new type of solution: the double scissor-pair.[23] This component enables three-dimensional assembly without losing the important property of non-uniform behaviour. The discovery of this novel scissor-pair component is the result of an experimental study in which existing solutions are methodically modified and analysed in search of emergent properties and behaviours.[24] As shown in figure 5, the double scissor-pair component corresponds, simply, to the use of two off-centre components, but according to a specific proportion - determined by x and y - between their scissor hinge positions. By changing the relation between x and y, it is possible to define several types of components and therefore different shapes and transformations. According to a specific x and y relation, two compatible components can be created: S1 and S2, which are mirrored version of each other. These two versions can be combined in arrays to create two- and three-dimensional configurations. The most important feature of this novel component is that, while keeping the off-centre quality of non-uniform behaviour, the lines A-B and C-D keep parallel to each other during transformation and, therefore, three-dimensional assembly is possible.

Figure 6 explains how three-dimensional assembly is possible. S1 and S2 can be combined in four different ways creating four modules - M1, M2, M3 and M4 - that can also be combined to create larger configurations. The three-dimensional connection is possible by using a cross assembly that enables linear and perpendicular assemblies among components.

Thicknesses have been incorporated into a digital model to design the parts for physical fabrication. Additional constraints are considered, such as the problems of overlapping, pivots and tolerances. Figures 7 and 8 show the physical prototype that has been fabricated in 1/8” aluminium. Each rigid and straight part is 12 cm long and 12 mm wide, the complete prototype is approximately 16 x 14 cm in its retracted position and 40 x 4 cm in its deployed position. A water-jet cutter has been used to machine the parts, which have then been manually assembled using ball-bearings and screws for each pivot assembly. The rigidity of the parts and the smooth rotation of ball-bearings are important to assure the single-degree of freedom of the mechanism, the single actuation and the synchronised propagation of movement from one component to another. The working prototype is a proof that supports and confirms the initial geometrical discovery of the double scissor-pair component, now in the physical world.

Even though real-world behaviour has been predicted through parametric model simulation and analysis, the physical prototype displays a strange behaviour in the last states of deployment. The behaviour changes drastically after approximately 70% of deployment. Figure 9 demonstrates this particular process. It is possible to appreciate the path described by one double scissor-pair throughout transformation: From the retracted state [*r*] towards the in-between state [*i*] the pivots move in a positive direction, describing a predictable slope variation; yet after [*i*] towards deployed state [*d*] the process changes drastically: the pivots move in a negative direction, developing an extreme slope modification. In spite of this unexpected and novel type of transformation, the double scissor-pair physical prototype maintains the single-degree-

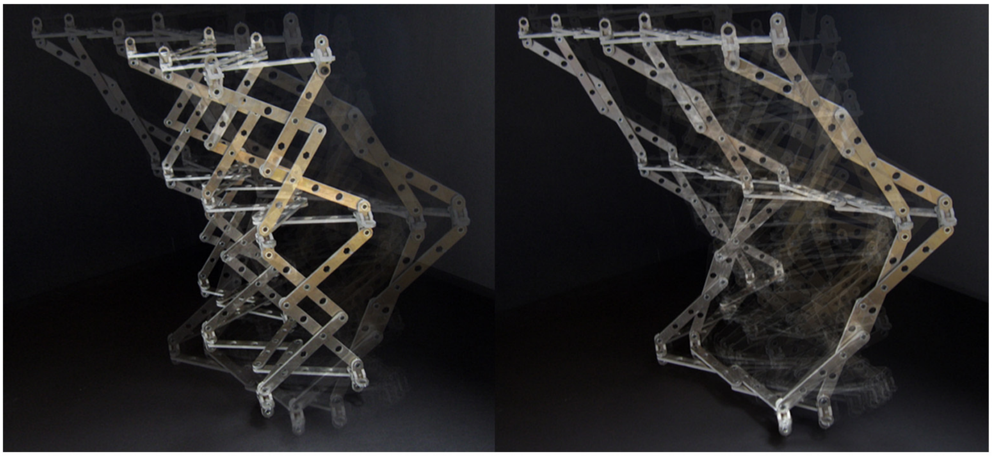

Fig. 7

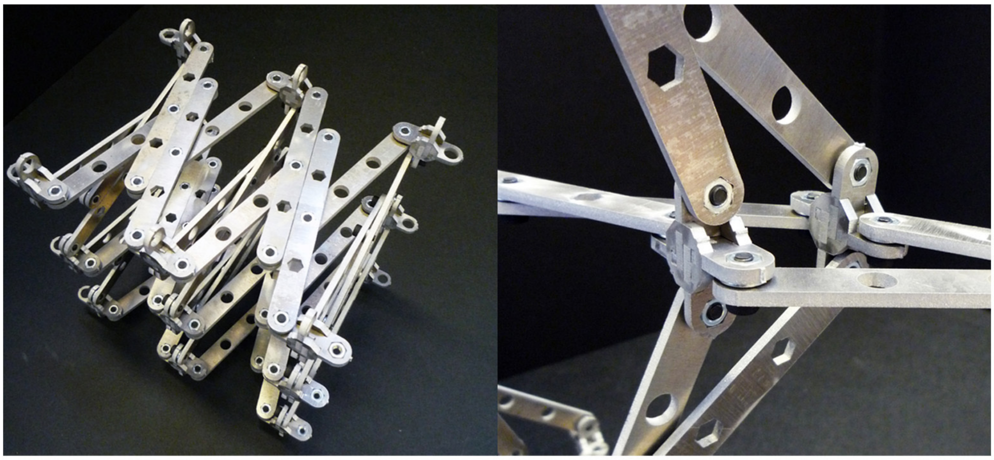

Fig. 8

Fig. 7: Double scissor-pair physical prototype.

Fig. 8: Double scissor-pair physical prototype (detail).

of-freedom advantages of previous scissor-pair solutions: it offers a non-uniform and surprising transformation - and, therefore, a range of alternative shapes - physically in three-dimensional space and with single actuation.

As shown in figure 10, the double scissor-pair aluminium prototype is able to transform its shape in a vertical configuration. This transformable three-dimensional structure can be envisioned as an architectural element: a vertical partition able to change its shape and generate indeterminate separations among spaces. Figure 10 shows how the vertical elements of the structure can be considered as two double scissor-pair components producing an additional behaviour: during transformation the system may allow modular disconnection generating structural discontinuity, fissures and openings. This new capability may add interesting architectural possibilities to the system: the process of transformation would not only divide and delimit space, according to different shapes, but also would enable a variety of fissures to be opened and closed by the users.

Enabling the Choice

User's choice

Indeterminate buildings could be conceived as live structures that transform their shapes according to a process of mutual interaction with their users. Within this vision, the building corresponds to an ambiguous, malleable and initially purposeless environment defined partially by the designer and partially by the user. The designer proposes a range of possible solutions enabling the users' choice, according to incidental and variable individual and collective needs, demands and desires. Both sides of the equation are needed: the final shape is the result of this mutual and continuous interaction between the possible solutions offered by the designer and the selection of some of them by the user.

According to Archigram the design of indeterminate buildings, which offers a range of possible solutions, enables the users' choice according to incidental needs, demands and desires. In a manifesto proposed in 1966 Peter Cook invites the user to be an active agent in the definition of the building, by stating: what you want when you want.[25] For Archigram, the determination of the built environment is no longer left in the hands of the designer of the building but rather it turns to the users, enabling them to choose what they want whenever they want: 'Architecture can be much related to the ambiguity of life. It can be throw-away or additive; it can be ad-hoc; it can be more allied to the personality and personal situation of the people who may have to use it.'[26]

In that sense, indeterminate buildings could be designed as machines that interface between the environment and the users. Archigram uses theories and technologies proposed by Cybernetics, defined in 1947 as the scientific study of control and communication in the animal and the machine.[27] Archigram's Control and Choice project, proposed by Peter Cook and Ron Herron in 1967, exemplifies how the cybernetic vision is translated to the control of buildings in real-time according to the input/output machine's capabilities. The Control and Choice project is a responsive mechanism composed of a tartan grid of tracks, which enabled the delivery of different services when needed. However, more interestingly, this responsive mechanism is covered by a rippled skin able to expand and contract according to the internal pressures, the movement of the deliveries and the users' demands.

Similar to Archigram's notion of buildings as cybernetic machines, Zuk and Clark consider buildings as responsive mechanisms able to transform kinetically.[28] They relate several ideas, developed in the sixties in construction, engineering, robotics and aerospace, which implied the control of a certain transformable behaviour through mechanical movement and sensory-motor capabilities. For Zuk

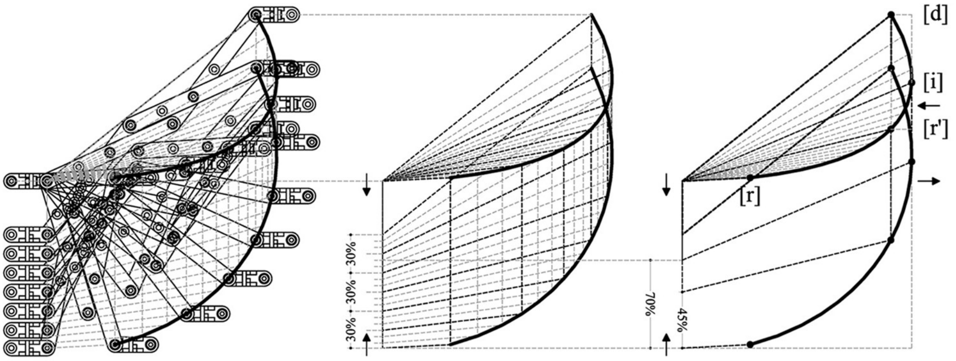

Fig. 9

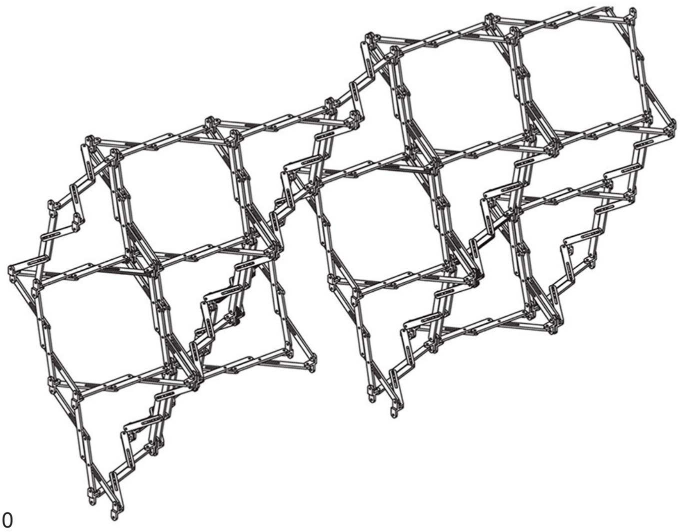

Fig. 10

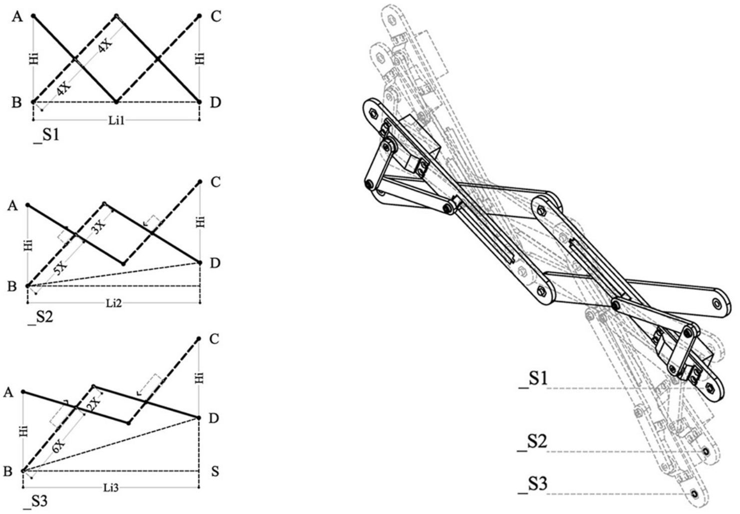

Fig. 11

Fig. 9: Non-uniform transformation of the double scissor-pair component.

Fig. 10: Architectural application: Transformable partition.

Fig. 11: Actuated double scissor-pair component and in-between states S1, S2 and S3.

and Clark, architecture can be defined as a ‘three-dimensional form-response to a set of pressures’ and, therefore, kinetic architecture corresponds to the shape modification according to the change on these pressures.[29] In this case, the input corresponds to these set of pressures, and the outputs to the shapes, within the range of alternatives, enabled by the transformable building.

According to Zuk and Clark, future change cannot be completely predicted or predetermined during design conception, and a kinematic architecture, based on movement, variation and control, will be partially the product of chance.[30] However, the range of possible solutions offered to the user is still restricted by the input/output capabilities of the building-machine. The users can only chose within a fixed and predefined range, wherein the building is not an indeterminate machine but rather a predetermined and predictable one, because it offers the same output according to the same input. Even though, the design of transformable structures offers a range of possible states to be chosen freely by the user, it is not possible to change the behaviour of the machine once built. In other words, the users cannot program the type of behaviours, the input/output relation, as they want whenever they want.

Learning from the real-world

Instead of predefining the behaviour of the machine, some Artificial Intelligence (AI) theories and techniques show how this behaviour can be defined by interfacing with the environment in real-time. In these approaches, the theoretical understanding of the real-world phenomena is assumed as incomplete and uncertain and, thus, neither predictive nor simulation models are used. These AI theories and techniques extend machine control to artefacts in which the relation between input and output is not fixed and can be defined and redefined in real-time without preconceived representations of the world. Even though these theories and techniques have been used in AI to engineer complex robotic systems, they have great potential when applied to simpler architectural machines able to change their behaviour in real-time according to emergent situations.

In the paper “Intelligence without Representation”, Rodney A. Brooks proposes the concept of Subsumption Architecture: a methodology of task-decomposition in which multiple goals are organised in layers, with neither central representation nor preconceived models of the world.[31] Brooks proposes autonomous robotic agents called Creatures which have to be designed to cope with changes in their environment and adapt to fortuitous circumstances. For him, it turns out to be better ‘to use the world as its own model’,[32] and therefore instead of predefining the overall behaviour, Brooks lets the Creature simply move around and interact with its environment through perception and action. For example, an initial layer can be used to *avoid* unexpected obstacles the robot may encounter in the environment, using sensors to detect obstacles and motors to turn and move in another direction. Another layer can be added to *explore* by looking at distant places and trying to reach them, using the same sensors and motors in parallel with the previous layer. An interesting observation here is that the Creature behaves - avoids and explores - without having a pre-defined representation, by simply interfacing with the world through perception and action. Likewise, each activity is an incremental layer of intelligence, which in parallel achieves different goals at the same time.

Learning by Recording Cases is another AI technique that considers real-world phenomena to be uncertain, and therefore the system is designed to self-sense, learn and enhance its behaviour by practice. Learning by Recording Cases is a technique that has been applied to the design of task-level robots to move an arm, swing a pendulum and throw or juggle a ball.[33] In these systems, the torque variation for each actuator is unpredictable, and therefore

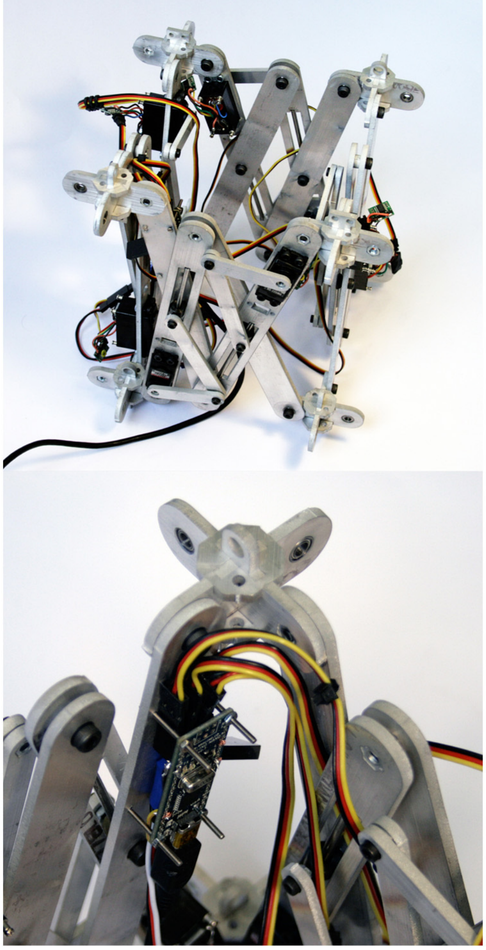

Fig. 12

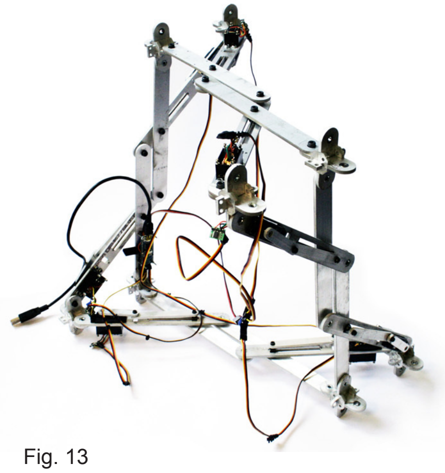

Fig. 13

Fig. 12: Physical Model: linear servo mechanisms controlled by an Arduino.

Fig. 13: Physical Model: S3 in deployed position.

the actuations are not predefined and instead are learned through practice.[34] For example, a robotic arm moving along a given trajectory illustrates how a system can learn by recording its own behaviour and according to real-world factors. The robotic arm begins with random and erratic movements. Consequently, data is recorded and then related to the desired trajectory. Learning Algorithms are used to make classification and predictions and then, by iterating the whole process, the system is able to progressively improve its performance reaching a satisfactory result.[35] The robot is designed for indeterminacy through setting up a system able to define and re-define its behaviour in the real-world through practice.

The concepts of Subsumption Architecture and Learning by Recording Cases illustrate how to envision indeterminate machines that remain in an open-ended process of definition and redefinition through time. This radical approach can be extended to the design of indeterminate buildings-creatures able to change their shapes and behaviours according to emergent situations. While Subsumption Architecture can be applied to simple sensory-motor architectural components that work in parallel and that perceive and act according to users' incidental needs, demands and desires, Learning by Recording Cases can radicalise that process through enabling permanent learning and even overriding and re-programming the machine's behaviour in real-time.

Experiment 02: Changing the transformations

The double scissor-pair component offers a range of possible solutions that enable the users' choice: A variety of possible non-uniform shapes controlled by single actuation. This great advantage of single actuation, nevertheless, represents a restriction since only one type of transformation is possible. Even though the double scissor-pair allows a non-uniform space of possible solution states, the transformation is predetermined since the same input generates the same output. It is not enough to offer a fixed space of possible solutions, but also to enable the user to choose what type of transformations the systems would produce. In order to radicalise the indeterminacy of scissor-pair transformable structures it is necessary to incorporate additional degrees of freedom to be controlled by sensory-motor actuation.

The centre and off-centre solutions can be related by incorporating an additional degree-of-freedom to the double scissor-pair solution. Actually, the off-centre component corresponds to the modification of the scissor-hinge from the centre to off-centre position. Therefore, by considering that modification as a slider, the double scissor-pair component would be able to transform from centre to off-centre position and vice versa. This actuated double scissor-pair solution emerges from combining the centre and off-centre solutions, wherein both are basically two states within a range of continuous transformation.[36] Figure 11 shows these in-between states - S1, S2 and S3 - and the physical actuated double scissor-pair component as well.

Since the double scissor-pair solution is actually two off-centre components, it is necessary to incorporate two linear actuators. The objective here is to generate new shapes and behaviours in real-time, extending the design process to the real-world. Therefore, the system has to be capable of being programmed and reprogrammed in real time through sensing human input and reproducing it as physical output. According to those capabilities, the system has to fulfil the following requirements:

- A-Sensing: In passive mode, the motors have to work as sensors to record the rotation, defined by the user in real-time.
- B-Actuating: In active mode, the motors have to reproduce the transformation, recorded throughout the sensing process.
- C-Processing: The relation between passive and

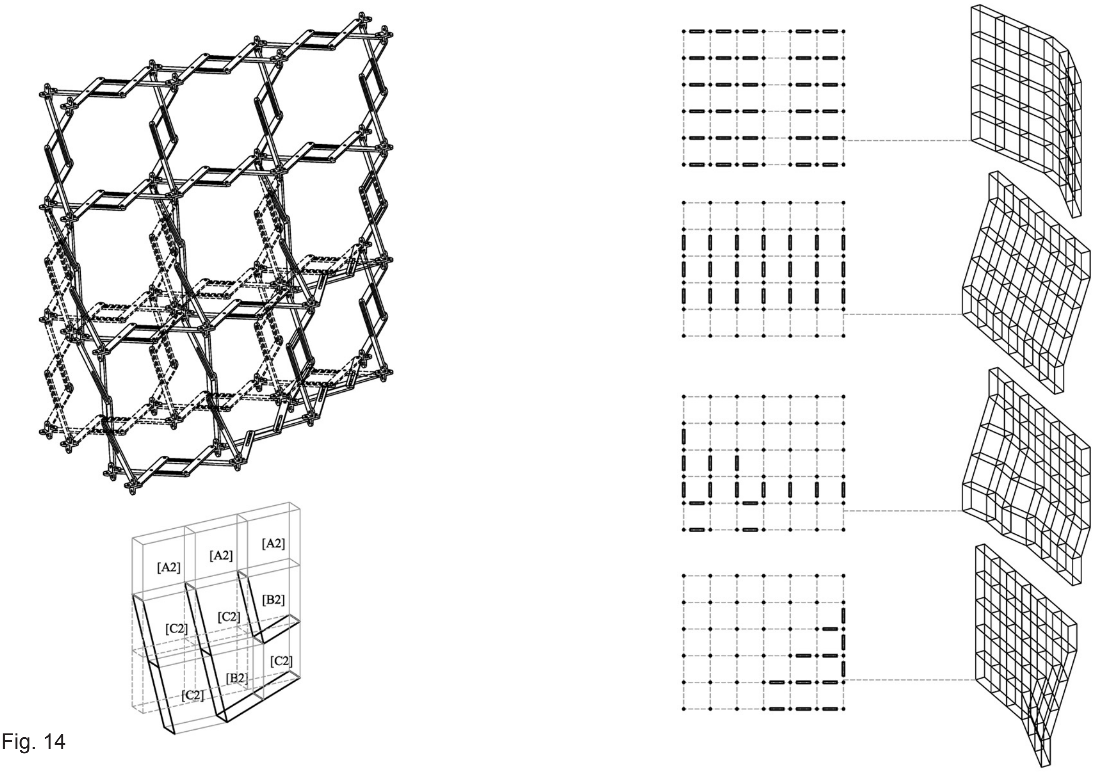

Fig. 14

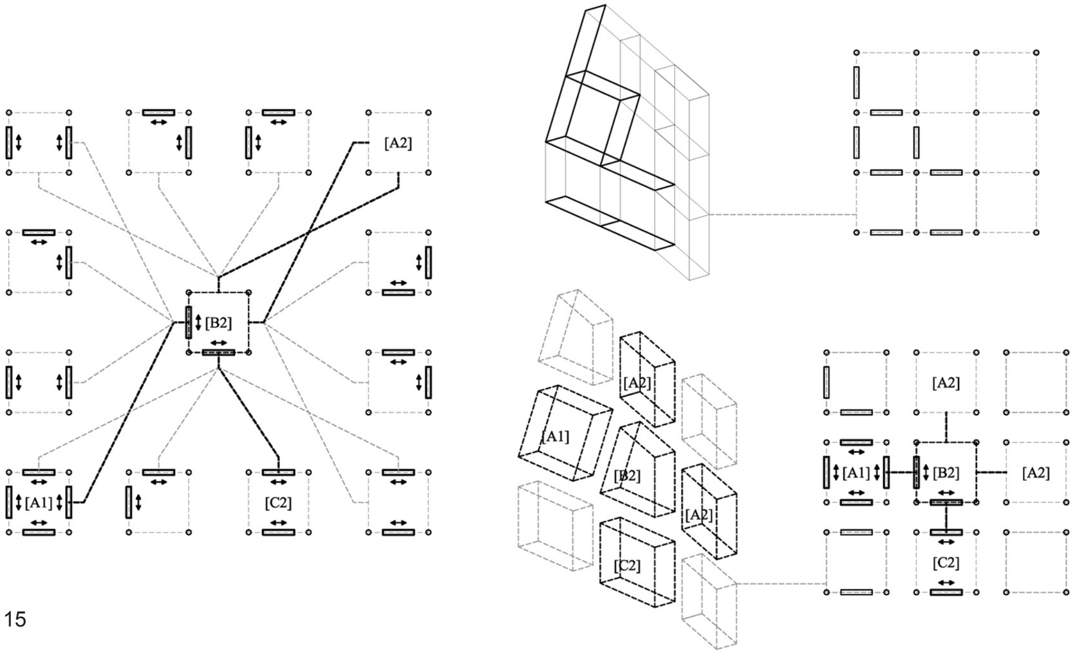

Fig. 15

Fig. 14: Partial actuation and different type of transformations.

Fig. 15: Sensory-motor control using constraint propagation.

active mode has to be overridden and reprogrammed in real-time.

A servo mechanism is used to fulfil the requirements of sensing and actuating by connecting a servo motor to a two-member-linkage and a sliding member. This system works as a linear-servo actuator that uses the servo's internal potentiometer to sense, and the servo's DC motor to actuate. This processing operation is controlled by an Arduino microcontroller that is embedded in the structure [figs. 12 and 13]. Even though a traditional servo motor works, by default, in active mode, the linear-servo actuator is capable of sensing during passive mode as well. The scissor-hinge's position can be modified in real-time since, during passive mode, the DC motor is turned off, and using the internal potentiometer to sense the rotation and to use that data as input.

Through the assembly of the actuated double scissor-pair component it is possible to generate new types of two-dimensional and three-dimensional scissor-pair transformable structures. Now, since there is an additional degree-of-freedom, which is controlled through the linear-servo actuator, it is possible to follow alternative states with no unique transformation. The transformation is no longer single-valued due to its capability of following multiple trajectories or lines of behaviour. In figure 11, it is possible to observe that the in-between states S1, S2 and S3 have the same in-between height Hi. This property is fundamental for three-dimensional assembly, since it will enable the combination of different states, in different directions, and, more importantly, the partial actuation of the structure. Figure 14 shows that certain behaviours require more actuation than others. The designer may want to optimise a certain number of actuators, allowing the system a certain degree of uncertainty. In this case, the advantage is that less actuation generates a double-curved configuration, which may be aesthetically interesting for the designer and the user.[37]

Nevertheless, the structure is a closed-chain mechanism[38] and, therefore, there is a problem of three-dimensional combination and coordination of the different actuations in parallel. However, instead of modelling, predefining and restricting local actuation and overall behaviour beforehand, the Learning by Recording Cases technique is used to learn from the interaction between mechanical constraints and user input: the double scissor-pair components are organised in independent modules, which are then programmed to sense, record and learn from the real-time input defined by real-world constraints.

Likewise, the Subsumption Architecture method is used to coordinate the relation between local input-output processes. Figure 15 specifies how the components, organised in modules A1, A2, B2 and C2, can be considered as individual Creatures able to work independently, yet in response to their neighbours. Each module has four sides, wherein actuation may or may not be applied. The constraint is that this behaviour, the actuation of each module's side, has to be coordinated to perform overall transformation. The central module B2 is chosen to illustrate this constraint process. Figure 15 demonstrates that for each B2 side, there are four possible corresponding states. Therefore, if the central module is transformed from A2 to B2 there are only four possible neighbours per side offering 16 possible alternatives to be combined. This process can be explained as a constraint-propagation problem in which the definition of one state defines certain alternatives, which likewise, once chosen, requires running the process again, in a recursive way. Therefore, even though the goal of overall transformation is indeterminate, the process can be reduced to the behaviour of one chosen module, in this case the central module that transforms from A2 to B2.

This approach is important since the objective is to respond locally according to users' input in real-time. The notion of the system as a decentralised modular robotic structure enables the generation of overall behaviour through local interaction with the

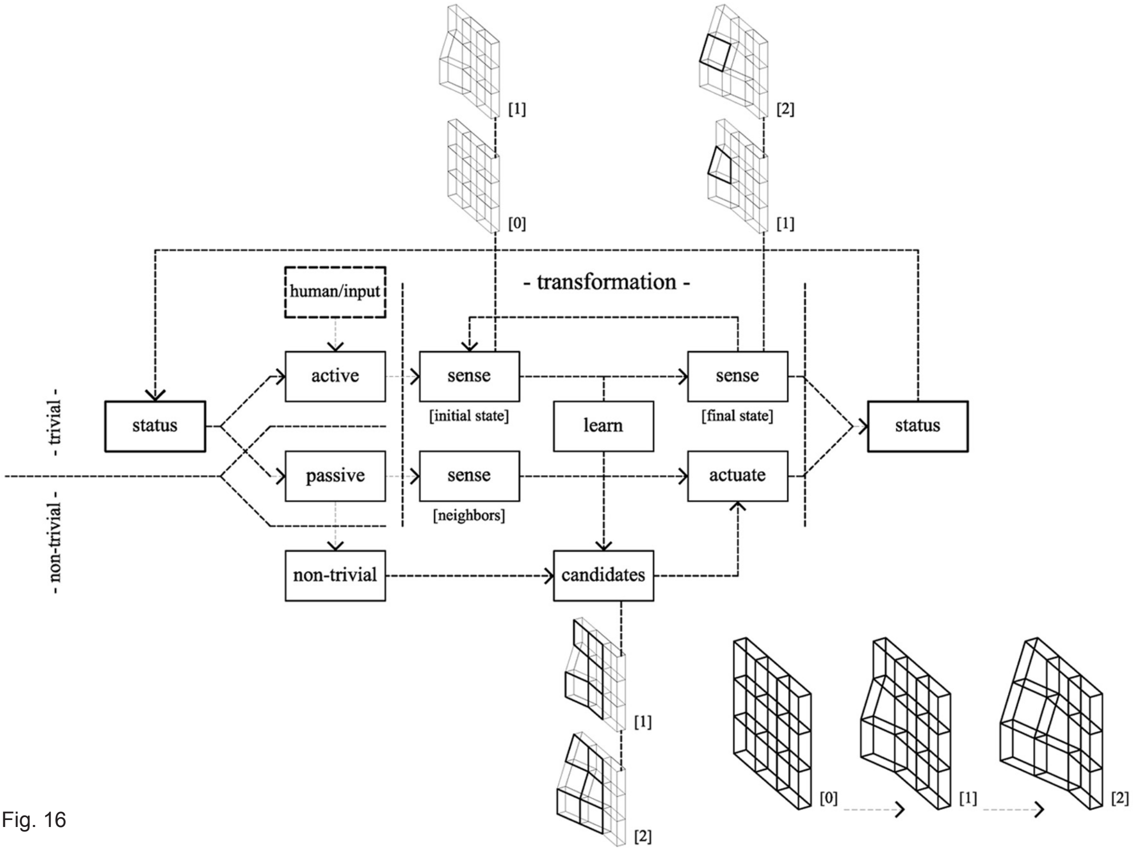

Fig. 16

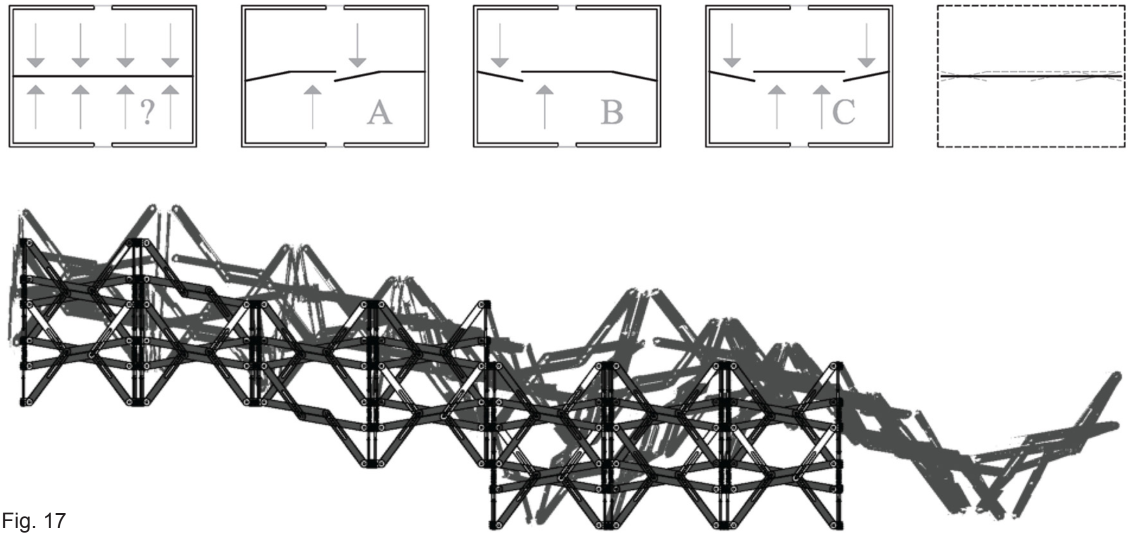

Fig. 17

Fig. 16: Activities in parallel: trivial and non-trivial behaviours.

Fig. 17: Architectural application: sensory-motor indeterminate partition.

user in real-time. The shapes and behaviours are uncertain for the designer, who is only responsible to set up a system capable of being defined and re-defined by the user in real-time. Indeterminacy is addressed through the task-decomposition method, according to two tasks, organised in parallel layers, as follows:

- A-Trivial behaviour: Responds to users' expectations, behaving according to the demands in a predictable way. In this case, the user gives some inputs and, after observing the outputs, is able to predict how the structure is going to transform.
- B-Non-trivial behaviour: Does not respond to users' expectation, behaving in unpredictable ways in order to promote unexpected outcomes. In this case, the user is not able to understand how the structure works and therefore, for the user, the transformations are always new.[39]

What must be noted is that the first layer, the trivial machine, is the default mode, and that the non-trivial mode only operates when the user is willing to obtain indeterminate outcomes. Figure 16 explains the process of activity decomposition in robotic scissor-pair transformable structures. The diagram shown in Figure 16 is based on constraint propagation, explained in Figure 15. Each module has to process the loop independently since the system is locally controlled by a microprocessor. There is no central control and the modules operate according to the user's input, during passive mode, and according to their neighbours during active mode.

The process launches in a trivial mode by checking the status of a module. If there is human input, the system is set in passive mode, wherein actuators are turned off in order to sense the transformation from state [*0*] to state [*1*]. Otherwise, the system is set in active mode and through the constraint propagation, explained in Figure 15, the system has to find a proper module candidate and actuate accordingly. In the beginning, the system will choose arbitrarily, and may appear erratic to the user. Yet through practice, the system will learn what types of states are chosen by the user and likewise how to optimise the number of actuations. Nevertheless, this learning process may be overridden every time the user is willing to get unexpected shapes and behaviours. By activating the non-trivial mode, the possible candidates are, again, modified arbitrarily. Likewise, because the human input is applied locally, the non-trivial behaviour may emerge in other regions of the structure and not necessarily in neighbouring modules.

The arrangement of the double scissor-pair components in modules enables disconnection and structural discontinuity, creating a range of possible indeterminate openings and connections between both sides of the structure. However, with sensory-motor actuation the shape and position of the fissures are not predetermined nor fixed anymore. Now, instead of deciding the final shape of a vertical partition and the location of the openings and connections between one side and the other, it may be possible to define a range of possibilities and different ways to open and close the structure as a whole: a malleable and indeterminate partition that can be opened, closed and changed with need, according to functional and aesthetic criteria controlled and chosen in real-time [fig. 17].

Conclusions

The objective of this paper was to convey the uncertainty that designers confront about the future situations their designs may encounter and may produce once built and throughout time. The vision was proposing the design of indeterminate solutions. Instead of designing unique fixed and ideal solutions, the new direction proposes transformable environments able to offer a range of alternatives to be defined and redefined by the users in real-time: An indeterminate architecture, sympathetic to uncertainty, incompleteness and emergent situations, wherein the building is reduced to an ambiguous, ephemeral and almost immaterial building environment.

It was argued that the design of an indeterminate architecture was the result of extending the design process to the real-world, by designing a range of alternatives to be selected in real-time by the users. The paper was organised around these two main ideas: Designing the Range and Enabling the Choice. For each section, a theoretical background about indeterminate architecture is presented - to introduce the concepts, problems and directions - followed by a technical background, involving engineering and AI methods - to materialise and radicalise indeterminacy - and an empirical experiment - to propose some novel architectural applications.

As regards the theoretical background, while Archigram's ideas and projects explained the origin of indeterminacy and showed some radical architectural applications, kinetic architecture expressed the advantages and limitations of an indeterminacy fostered by the design of transformable buildings. In relation to the technical background, while some engineering solutions demonstrated how to materialise a range of states by using scissor-pair transformable structures, some AI methods illustrated how to radicalise users' choice by machine control in real-time. Existing scissor-pair transformable solutions were analysed by exploring the in-between states, the range of possible shapes within the transformation. Subsumption Architecture theory and Learning by Recording Cases technique demonstrated how a machine could interface directly with the real-world, without predetermined representation, and how it could self-sense, record and learn from its own performance and interaction with the world. Finally, the empirical experiment used the architectural and technical background to explore the boundaries of indeterminacy within architectural design. The experiment aimed at radicalising indeterminacy as much as possible, by searching for non-uniform transformations, to extend the range of possible solutions, and for techniques to enable the user's choice and modification of the machine's behaviour in real-time. A novel scissor-pair component was presented along with the digital and mechanical system to radicalise its indeterminate capabilities.

Even though the theoretical, technical and empirical work was successful in stating the problem, showing initial answers, direction and applications, there are some ends yet untied that are valuable in delineating the scope of future research. First, the theoretical background referred only to the origins of the concepts and ideas within a limited framework. Future work will be conducted to incorporate additional concerns such as the problem of continuity from conception to materialisation. Designing an indeterminate architecture, as a continuous process from design conception to the life of the building, has to redefine the traditional architectural gap between what is designed and what is then built and used.

Second, even though the technical background offers an initial insight into mechanical transformation and actuated control, the way in which these processes should be translated into architectural applications was not clearly stated. It is important to find proper ways to interact with the building environment and, likewise a proper timescale for the transformation. Future work will be undertaken to study human-machine-building interaction, and how the scale of a building may imply a speed of transformation similar to the one in natural processes, such as seasonal transformations in trees, sea tides, sun, or cloud movements.

Finally, the empirical experimentation with sensory-motor control was not completely implemented. It is still necessary to find a proper way to actuate a structure with economy of actuators, and to implement the software aspect through the use of learning algorithms and layering control. Likewise, the exercise only resolves a particular application within the restricted framework of scissor-pair solutions. It is necessary to propose general deliverable principles to be applied in other types of transformable solutions. The empirical experiment will not be a contribution if it is not possible to use its principles in other explorations. Therefore, there is a need for further investigation into how this particular experiment can define general principles and solutions beyond its own particular technical problems and theoretical implications.

Notes

1. This paper is based on the Master of Science dissertation I developed at the MIT Computation Group. See: Daniel Rosenberg, *Designing for Uncertainty: Novel Shapes and Behaviors using Scissor-pair Transformable Structures* (Cambridge: MIT Master of Science Thesis, 2009).
2. Simon Sadler, *Archigram Architecture without Architecture* (Cambridge: MIT Press, 2005).
3. William Zuk and Roger Clark, *Kinetic Architecture* (New York: Van Nostrand Reinhold, 1970).
4. Robert Kronenburg, *Flexible: Architecture that Responds to Change* (London: Laurence King Publishers, 2007).
5. Non-uniform behaviour refers, in the context of this paper, to transformations wherein the in-between states correspond to different shapes. A uniform behaviour, on the contrary, refers only to transformation wherein the in-between states are scaled versions of each other.
6. Sadler, op. cit., p. 94.
7. Peter Cook, *Archigram* (New York: Princeton Architectural Press, 1999).
8. Sadler, op. cit., p. 89.
9. Zuk and Clark, op. cit., p.11.
10. Zuk and Clark, op. cit., p. 98.
11. For an introduction on kinematics, see: Franz Reuleaux, *The Kinematics of Machinery* (New York: Dover Publications, 1963).
12. Z. You and S. Pellegrino, 'Foldable Bar Structures', *International Journal of Solids and Structures* (1996), 1825-47.
13. Charles Hoberman, Radial expansion/retraction truss structures (US patent no. 4942700, 1990).
14. For movable theatre structures, see: Emilio Perez Pinero, Three-Dimensional Reticular Structure (US patent no. 3185164, 1965)
15. For expandable space structures, see: F. Escrig, 'Expandable Space Structure', *Internation Journal of Space Structures* (1985), 79-91.
16. For collapsible portable shelters, see: Theodore Zeigler, Collapsible Self-Supporting Structure (US Patent no. 3968808. 1974).
17. For deployable domes, see: Hoberman, op. cit., and You and Pellegrino, op. cit.
18. For retractable roof structures, see: Thomas Buhl, Frank Jensen, and Sergio Pellegrino, 'Shape Optimization of Cover Plates Retractable Roof Structures', *Computers and Structures* (2004), 1227-36.
19. For centre scissor-pair solutions, see: G. Edwards, Expanding apparatus for fire escapes (US Patent 415667, 1889); G. Luckey, Nesting three-dimensional lazy tong structure (US Patent no 3672104, 1972); and
20. For off-centre scissor-pair solutions, see: F. Escrig and J.P Valcarcel, 'Geometry of Expandable Space Structures', *International Journal of Space Structures* (1993), 79-91.
21. For angulated scissor-pair solutions, see: Hoberman, op. cit., and You and Pellegrino, op. cit.
22. For more detail see: Rosenberg, op. cit.
23. This double scissor-pair solution is novel because it transforms from planar to double-curved three-dimensional structures while deploying. Other double scissor-pair solutions are intermediate elements that enable the deployment of single-curved profiles. See: Z. You, 'Deployable Structure of Curved Profile for Space Antennas', *ASCE Journal of Aerospace Engineering* (2000), 139-43.
24. For details on the experimental modification of scissor-pair solutions, see: Daniel Rosenberg, 'Novel Transformations of Foldable Structures', *CAADRIA: Between Man and Machine* (2008).
25. The statement 'what you want when you want' appears

in a cartoon made by Peter Cook in 1966 to explain the Control and Choice ideas. See: Cook, op. cit., pp. 68-69.

26. Peter Cook, *Experimental Architecture* (London: Studio Vista, 1970), p. 67.
27. Norbert Weiner, *Cybernetics* (New York: John Wiley & Sons, 1948). It is important to clarify that the translation of Cybernetics to the control of buildings in real-time does not refer here to recent developments in Intelligent Buildings. Rather, this translation refers here to the control of kinetic buildings able to change their shape according to variable demands. For information on Intelligent Buildings, see: Derel Clements-Croome, *Intelligent Buildings: Design, Management and Operation* (London: Thomas Telford, 2004).
28. Zuk and Clark, op. cit.
29. Zuk and Clark, op. cit., p. 5.
30. Zuk and Clark, op. cit.
31. Rodney Brooks, “Intelligence without Representation”, *Artificial Intelligence* (1991), 139-59.
32. Brooks, op. cit., 140.
33. Eric Aboaf, *Task-level Robot Learning* (Cambridge: MIT Master of Science Thesis, 1988).
34. Patrick Winston, *Artificial Intelligence* (Cambridge: Addison-Wesley, 1992).
35. Aboaf, op. cit.
36. Rosenberg, 2009, op. cit.
37. It is important to clarify that the additional degrees of freedom are activated locally and do not necessarily affect the whole structure. Likewise, the scissor-pair’s property of single-degree-freedom is not lost, as it is used once a particular proportion between x and y is defined and momentarily fixed by the local actuation.
38. In a closed-chain mechanism the last component is connected to the first and, therefore, the coordination of actuations according to the mechanical arrangement is critical. See: Ranjan Vepa, *Biomimetic Robotics Mechanisms and Control* (New York: Cambridge University Press, 2009).
39. For Heinz von Foerster’s definitions of trivial and non-trivial machines, see: Lynn Segal, *The Dream of Reality: Heinz von Foerster’s Constructivism* (New York: Springer-Verlag, 2001).

Biography

Daniel Rosenberg studied at the Catholic University of Chile, receiving his professional degree in Architecture in 2003 and a Master in Architecture degree in 2005. From 2004 to 2007, he worked as a professional in his own architectural office - called W.A.R. - and as professor of architecture at the Catholic University of Chile. In 2007, he moved to the Massachusetts Institute of Technology where he completed a Master of Science in Architectural Studies (SMArchS) degree in the Design and Computation program. He is continuing his studies in this program as a PhD student.

Kinetic Digitally-Driven Architectural Structures as ‘Marginal’ Objects - a Conceptual Framework

Sokratis Yiannoudes

Introduction

Although kinetic architectural elements and structures have existed since antiquity and in different cultures,[1] they were more widely recognised and developed throughout the second half of the twentieth century due to the rapid changes in the western way of life.[2] In particular, from the Second World War until recently, transformable lightweight structures and deployable, mobile or portable environments, built by architects and firms such as Buckminster Fuller, Hoberman associates and FTL Happold to name but a few,[3] have sought to resolve economical, practical or ecological problems[4] of the construction industry, and respond to issues of survival or nomadic dwelling.[5] On the other hand, in the 50s and 60s, the development of computers and cybernetic control systems, inspired the design of more experimental transformable environments - such as Price’s *Fun Palace*, Archigram’s *Living 1990* installation and Constant’s *New Babylon* - able to respond to change and individuality. Such visionary projects would not result in realised architecture, yet they were precursors of the so-called ‘intelligent environments’, the applications that emerged, since the beginning of the 90s, from the ambient intelligence vision, i.e. the distribution of ubiquitous digital technologies in physical space.[6]

Lately, the merging of kinetic architectural systems and digital technologies has produced digitally-driven kinetic architecture, structures, environments or building components able to modify the shape, size or position of their physical form using embedded computational technology. This is a vision for technologically-enhanced architecture with ‘naturalised’ capacities - that is, sensing and actuation abilities, intelligence, motion and pro-active behaviour. Although such applications are rather limited and exist mostly in experimental and academic contexts, there is indeed a growing interest in the potential development of digitally-driven kinetic architecture. As Michael Fox of the Kinetic Design Group argues:

> *Architects need to design with an understanding of the current capabilities of embedded computation that have attained sufficient maturity to act as independent subsystems that can be beneficially incorporated into kinetic design.*[7]

It is widely accepted that the primary goal of digitally-driven kinetic structures is to provide flexible adaptation to constantly changing needs, desires,[8] and environmental conditions (optimisation and control).[9] A part of the online text in the *Muscle Room* (a kinetic space by the Hyperbody Research Group) website reads:

> *The Muscle Room envisions a concept where the user can alter his surroundings to suit his every need. When the room is entered it is completely empty. One big, open space. By interacting with the room the user can get a different layout or appearance.*[10]

Similarly, Michael Fox and Bryant Yeh explain:

> *This research develops a concept for the application of smart environments to kinetic systems in architecture. The goal is to create flexible and responsively adaptable architectural spaces and objects… Intelligent kinetic systems are an approach for utilising technology to create architecture that addresses today's dynamic, flexible and constantly changing activities.*[11]

Konstantinos Oungrinis, in his research on kinetic architecture, proposed a digitally-driven architectural environment - the 'Sensponder' - which optimises adaptability by integrating all the different operational capacities of kinetic systems in architecture. His 'Sensponder' architecture would be able to adapt to changing functional, environmental and structural demands by acquiring information from all available sources (through various sensors), and respond by performing local actions based on optimised decisions.[12]

Yet, behind the obvious functional reasons for designing and constructing such structures, there is, in my view, another equally important cultural aspect that drives these designs. In this paper I will show that the motivation lies in a culturally-defined human tendency to challenge the boundaries between the animate and the inanimate or the human and machine. Thus, I aspire to anticipate a conceptual framework through which to reflect on their value. In the following I am looking into the way digitally-driven projects are conceived. As I will show, they are not only understood as functional objects but also as 'social beings'.

Digitally-driven kinetic structures: The E-motive House and the Muscle Tower II

Some of the most representative digitally-driven kinetic structures are those of the Hyperbody Research Group and its director Kas Oosterhuis at TUDelft as well as Oosterhuis' firm ONL.[13] Their projects Muscle Tower I and II, E-motive House, Muscle NSA, Muscle Body, Muscle Reconfigured and Trans_PORTs 2001, combine kinetic-mechanical systems with computer technologies. Other similar projects are those of the Design Research Lab at the Architectural Association exploring the potential of kinetic responsive structures in the urban context.[14] Maybe the most well-developed project in terms of feasibility, technical resolution and commercial potential is dECOi's Aegis Hyposurface, a moving responsive surface, a kind of kinetic information display, actuated by pistons. Although it is not an architectural space, it can be incorporated in architectural structures or urban areas to provide informational and advertising services as well as interactive sensory experiences.[15] Due to the limited scope of this paper I cannot examine the above examples one by one. Two of them, though, will be examined more closely here because they are highly illustrative of my argument: the E-motive House and the Muscle Tower II. Yet, the ideas discussed below apply to most of these projects.

Conceived as an information network node, the E-motive House [fig.1], designed by Oosterhuis and his ONL team, is a changeable structure (constructed by a complex combination of pneumatic and hydraulic cylinders, wooden beams and air chambers) able, in theory, to respond to the actions, needs and desires of both local and internet users. It will function in different ways: either as a space for work, food or sleep, thus realising something that would have seemed unconceivable in the past.[16]

However, besides the capacity to respond to changes of function, the description of the house includes a few other important characteristics. For Oosterhuis, the E-motive House is a 'being' with social skills and emotional states able to cooperate, learn, communicate and participate in social interactions with its residents. Because of the complex interactions between all the factors that affect its performance, the behaviour of the house will be unanticipated and seemingly unpredictable,

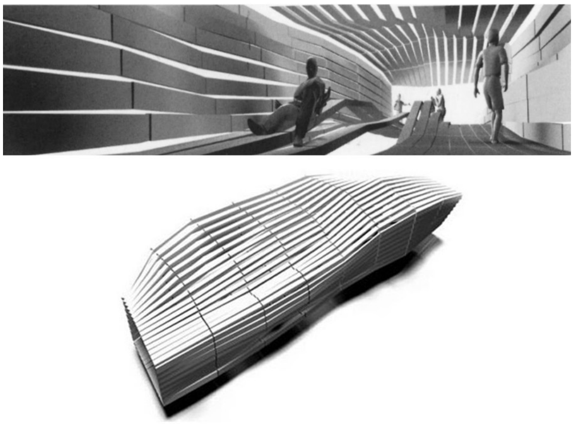

Fig. 1

Fig. 2

Fig. 1: E-Motive House, 2002

Fig. 2: Muscle Tower II, 2004

giving the impression of an emotional entity. It will incorporate intelligence, which will allow it, through interaction with people, to gradually develop a character and express a predefined series of psychological states (e.g. entertainment or educational state), challenging the residents to adapt to such an environment.[17]

Apart from functional flexibility, a number of other issues is mentioned with regard to the E-motive House here: learning, intelligence, pro-activity and intentional behaviour as well as the capacity for social interaction and cooperation for the production of experiences. Describing the E-motive House Oosterhuis mentions the possible objects of discussion between its residents:

> *What mood is your house in today? Isn't it feeling well? Why is your house behaving so strangely lately? Perhaps it needs to see a doctor? Did you care enough for your house? Is your house boring you? Are you neglecting your house? Is your house suggesting that you might be boring in the way you perceive it? These would be the sort of social conversation topics between the inhabitants of e-motive houses.*[18]

It seems that Oosterhuis attempts to attribute qualities beyond functional flexibility to the structure; he talks about it as if it is not just a soulless and inert environment but a 'living organism', a social, emotional being able to convey mood, a need for affection and communication. This attitude characterises the way he understands his other projects as well, for example the *Muscle Reconfigured* project:

> *An intuitive interaction, opinionated towards seamless information exchange is initiated through the research experiment, hence transforming everyday utilitarian space into an inter-activating responsive organism.*[19]

It is important to note here that the physical characteristics of these structures (form and motion) should play a role in such attributions. For instance, Oosterhuis' Muscle Tower II project, developed and constructed by the Hyperbody, 'looks' very much like a 'living organism' [fig.2]. A flexible frame consisting of a network of pneumatic actuator cylinders can stretch or contract, thus making the whole structure bend, swivel or twist in different points along its height.[20]

The range of movements that it can perform is limited to left-right and front-back shifts responding to the presence of visitors detected by its proximity sensors. A visitor's presence will make it bend towards his or her direction for 30 seconds and then continue to perform its pre-programmed movements.[21] Video demonstrations of the structure in action, which can be found on its web site,[22] show that, although the set-up is simple and its behaviour is based on on-off commands, the structure appears to react to human movements with unpredictable position and posture changes. Here, the actual experience of the moving structure - its sudden shifts of direction and orientation along with its humanoid yet abstract form - may perceptually convey the sense of life.

It is true that seemingly autonomous self-generated motion, reactivity, as well as a number of other factors contribute to the perception of objects as alive, animate entities.[23] One can easily assume, then, that architectural structures able to move, react, interact or self-act, may sometimes be perceived as animate. I will argue, however, that the tendency to see digitally-driven structures as 'alive' cannot be explained merely in perpetual-psychological terms, because the idea of architecture as a 'living organism' has been part of the language and conceptualisation of architecture since the 19th century, and lately a recurring concept in the descriptions of intelligent environments and computationally-augmented architecture.

Architecture as a 'living organism'

The use of biological metaphors and images within the architecture discipline is no recent phenomenon. Throughout the nineteenth century biological terms and metaphors (like 'circulation', 'structure' or 'function') were being used by architects in order to render aspects of architecture as objective categories that can be analysed with scientific methods.[24] However, the most important adoption of biological metaphors in architecture took place after the Second World War through the language and projects of the architectural avant-garde within the cultural, scientific and philosophical context shaped by cybernetics, Heisenberg's uncertainty principle and Karl Popper's attack on sociopolitical determinism.[25] For example, the avant-garde group Archigram, rejecting any conceptual boundary between the organic and the inorganic (echoing cybernetics),[26] designed architectural environments capable of responding to the indeterminacy of social and individual conditions[27] based on biological concepts such as 'transformation', a.k.a. 'metamorphosis'.[28]

While Archigram's approach to biological concepts in architecture was only iconographic, in Warren Brody's 1967 article 'The Design of Intelligent Environments', biological concepts such as complexity, self-organisation and evolutionary ability were regarded as inspirations for an active intelligent-responsive architecture able to learn from its users, self-act and anticipate behaviours based on acquired experience.[29] This relationship between architecture and life becomes even more literal today as the vision of ambient intelligence embedded in architecture has led to a rhetoric that describes intelligent environments that can move, perceive, interact, self-act and learn, as 'living', 'social' or 'intelligent'. In many cases intelligent environments are even conceived of and described as living entities and artificial beings. For instance, an article in *Wired* magazine mentions the ability of buildings to mimic living systems, perceive and react to environmental stimuli:

> *What if buildings could function like living systems* [...] *A building that mimics a living system would be able to sense and respond appropriately to exterior conditions like varying winds, temperature swings or changing sunlight.*[30]

Kynan Eng et al.'s ICRA 2003 conference paper describes the intelligent room ADA as an 'artificial creature',[31] whereas in another point the authors mention that 'the project Ada: intelligent space is an exploration in the creation of living architecture',[32] explaining how this environment is perceived by its visitors as alive. Stephen Jones speaks even more literally about the relationship between intelligent environments and organisms:

> *In developing intelligent environments we lose the distinction between organism and environment. The environment becomes an organism because it does all the things that an organism does except, perhaps, self-replication. The kinds of processes that must be operating in the integration of artificial organisms are analogous to those operating in biological organisms. These include complex self-regulatory processes enabled by substantial feedback circuits* [...] *These are the sort of things that a brain or nervous system does in response to its earliest experience.*[33]

Maria Luisa Palumbo points out that information technology links architecture to the living body:

> *The question of sensitivity now indissolubly links the body, machines and architecture. If the distinguishing factor between living and inorganic forms is essentially the capacity to exchange information with the environment and, consequently, flexibility in terms of the capacity to learn and modify, the key innovation of architecture in the second half of the 20th century, characterised by its growing intimacy with machines, is the aspiration to give buildings the sensitivity and flexibility of living systems.*[34]

In the following section I will open up this field of 'alive' objects that have been challenging the boundaries between the natural and the artificial by examining their practices and their presence historically. In this way I will be able to contextualise digitally-driven kinetic architecture within a wider practice and discourse that sees 'living' artefacts as what MIT professor Sherry Turkle has termed 'marginal objects'. These are objects built to interrogate the boundaries between human and machine, the biological and the technological, because they stand on the boundary between the living and the non-living.

'Living' technological objects as marginal objects

Although common sense allows us to distinguish between living and non-living objects and entities as belonging to different categories, this distinction is not as straightforward for computational objects that, because of their phenomenal attributes, stand on the boundary between these categories. Sherry Turkle names them 'marginal objects':

> *Marginal objects, objects with no clear place, play important roles. On the lines between categories they draw attention to how we have drawn the lines. Sometimes in doing so they incite us to reaffirm the lines, sometimes to call them into question, stimulating different distinctions* […] *Marginal objects are not neutral presences. They upset us because they have no home and because they often touch on highly charged issues of transition.*[35]

Turkle develops her argument by looking into the reactions of adults, children and scientists to the first appearance of computational artefacts in the wider society of the 1970s which gradually entered the social and psychological life of people, affecting the ways they understood and thought about life. It was difficult to classify such objects in terms of whether they were animate or inanimate (this will be examined further down). In this text I am using Turkle's concept to define digitally-driven kinetic architecture, which presents characteristics of living organisms (interaction, self-initiated motion), also as a marginal object. What I am presenting in the following section is a history of creation of marginal objects, in other words a history of contestation and redefinition of the boundary between biology and technology. I will thus attempt to argue that digitally-driven structures can also be placed in this same context.

Although actual examples and descriptions of marginal objects go back as far as antiquity,[36] they have only been part of philosophical and cultural discourse since the seventeenth and eighteenth centuries. During that time, automatic machines, a.k.a. 'automata', became part of philosophical and scientific culture, because, contrary to vitalism, mechanistic (clockwork) explanations of natural phenomena were extended to biological systems by Descartes' mechanistic philosophy and his successors. More radical materialist philosophers of the period, such as Julien Offray de la Mettrie, would go as far as describe not only bodily processes but also mental functions in terms of mechanism.[37] Yet, in Jessica Riskin's view, eighteenth-century automata, such as Vaucanson's Defecating Duck made to simulate the animal's physiological processes, expressed the philosophical dispute between the mechanistic and the non-mechanistic interpretations of life, by attempting to determine the extent to which living beings could or could not be reproduced by mechanism. According to Riskin they resulted in 'a continual redrawing of the boundary between human and machine and redefinition of the essence of life and intelligence'.[38]

Although, during the nineteenth century, vitalistic views on life remained active even in scientific contexts, they were disputed by the development of the steam engine and the energy conservation law which showed that living organic phenomena - the production of heat and its conversion into mechanical energy, respiration and metabolism -

were also phenomena of machines.[39] Later, in the mid-twentieth century the advent of cybernetics as well as molecular biology pointed to the view that human and machine, the organic and the inorganic, are all information-processing devices, systems that adapt and adjust to their environment on the basis of the flow and control of a common unit called information.[40] This attempt was partly successful because of the way information was conceived and constructed in the scientific community and because of the electromechanical devices that were built by cyberneticists to demonstrate their ideas in reality.[41] In effect, the theories and machines of the scientific community of cybernetics, although constructed, resulted in a synthesis of humans and machines and became the means to challenge and blur the boundaries separating the living and the non-living.

This same attempt to equate the organic with the machinic was later led by the Artificial Intelligence (AI) community, which either regarded the human mind as an information-processing device, just like a computer, or the human brain as an emergent system, a model for the neural network of the connectionist approach to AI.[42] Within both approaches, however, traditional boundaries and distinctions between the natural and the artificial would dissolve because humans and computers were conceptualised as either rule-based devices or non-deterministic systems.[43] Yet at the same time both scientists and non-scientists would adopt a critical stance against this equation, arguing that AI suggests a flat mechanistic view of human nature; their critique, which Turkle calls 'romantic', would assume that what separates humans from computers is exactly that which cannot be coded, namely emotion and spontaneity.[44]

Human-machine boundaries are also challenged today in the practices and discourses of Artificial Life (A-Life), where digital entities are designed to simulate biological processes. In particular, since the end of the 1980s, the field of digital A-Life (also called *soft A-Life*) has argued that life includes any possible form, either physical or digital, conceived only in terms of the self-organising complex processes (evolution, natural selection, adaptation, learning, physical interactions) that constitute it.[45] Such scientific conceptions and definitions of life, along with the way digital A-Life forms are represented and referred to, enhance the perception of biological and artificial life equations, constituting, as Hayles has put it, 'a multilayered system of metaphoric material relays through which 'life', 'nature' and the 'human' are being redefined'.[46] At the same time, however, some A-Life researchers have emphasised the importance of the material body - the physical structure of the organism - in the construction of artificial life.[47] Moreover, people's reaction to A-Life would emphasise sensuality and biological and physical embodiment as the basic constituents of life, separating them from A-Life objects.[48]

What seems to be dominant in this historical account of marginal-object production is the assumption that the boundary between human and machine is either unbridgeable - in the romantic reactions were there was always a parameter, like emotion, that enhanced those boundaries - or non-existent - in artificial-life practices or cybernetics where there were no ontological differences between the natural and the artificial. In other words, this boundary, although under controversy and dispute (sometimes blurred, sometimes clear-cut), was always present. As Warren Sack puts it:

> *...such critiques assign a timeless, unchanging structure to what is better characterized as an on-going struggle to negotiate the ways in which the 'artificial' flows into the 'natural' and vice versa.*[49]

It seems to me that digitally-driven architecture can be considered to be part of such a tradition of marginal-object production. I have already mentioned the ways in which this kind of architecture is conceived of or perceived in terms of human or biological attributes. Such attributes turn it into something more than a mere functional object; it becomes an object through which boundaries are interrogated, through which architecture acquires, once more, the status of an almost 'living' entity - a marginal object. But why do architects design digitally-driven kinetic structures endowed with such a status? To answer this question I will first have to answer the question why marginal objects are produced.

The most well-known reason for the production of artificial-life objects and images is the need to understand what is unique about man and what separates man from machines, as Bruce Mazlish[50] and Christopher Langton have explained.[51] It is, however, senseless to claim that the same reason applies for digitally-driven kinetic structures; although they present biological phenomena, like motion and interaction, they are not experimental simulations of biological processes, as is the case with A-Life objects. Digitally-driven kinetic architecture is not a scientific experiment but an architectural creation. Therefore, I think there is another reason driving the design of this kind of architecture that will become evident through the examination of the socio-cultural dimension of this phenomenon.

The following section attempts to respond to this problem and come up with a new conceptualisation of digitally-driven architecture, one which will no longer see it only as a functional object but also as a culturally-defined *quasi-object*.

The Nature-Culture separatism in modernity

Since the 1980s the social studies in science and technology have been challenging the dissociation between the natural and the cultural, the scientific and the social, the object and the subject prevalent in the last two centuries, exposing the hybrid forms with which things are represented. For anthropologist Bruno Latour modernity is a double process of 'purification', that is, separation of Nature (and science) from society and the self, and 'hybridisation', the mixing of nature and culture. Purification is what moderns pretend to be doing, Latour claims, because nothing is allowed to take place in-between nature and society (object and subject), the boundary that defines all reality, although in practice they produce all kinds of nature-culture hybrids (quasi-objects).[52] The modern accepts these hybrids but conceives them as mixtures of two pure forms, things and subjects or humans and non-humans, which he separates at the same time in order to extract from them the subject (or the socio-cultural) part and the object (or the natural) part.[53] This distinction is, for Latour, an imaginary construction because everything takes place between society and nature, in a 'middle kingdom' rejected by modernity - a central point of 'departure', not separation.[54] Modernity explained everything but left outside what was in the middle - the production of hybrid technological objects in a post-industrial era of information and 'smart' machines:

> *…when we find ourselves invaded by frozen embryos, expert systems, digital machines, sensor-equipped robots, hybrid corn, data banks, psychotropic drugs, whales outfitted with radar sounding devices, gene synthesizers, audience analyzers, and so on* […] *and when none of these chimera can be properly on the object side or on the subject side, or even in between, something has to be done.*[55]

A-Life is one of those intriguing practices where the modern subject-object distinctions are redefined. Lars Risan has noticed that although A-Life scientists construct artificial 'living' beings, at the same time they try to rid them of any subjectivity because they are considered to be scientific objects of inquiry. Yet, the difficulty in defining these distinctions, Risan thinks following Latour, is due to their use of everyday language which makes it difficult to draw subject-object boundary lines:

> *In our everyday language we - 'moderns' - have*

> *always been 'non-moderns'; 'witch doctors'; we do in practice endow our objects with a lot of subjective properties. Unlike, for example, physics, Artificial Life is a technoscience where it is hard to maintain a clear-cut boundary between everyday language and scientific models.*[56]

In his text, *Mixing Humans and Nonhumans Together: The Sociology of a Door-Closer*, Latour (using the nickname Jim Johnson),[57] discusses the problem of human-machine separation in the case of an automatic door-closer. He analyses how this purely technical object is clearly a moral and social agent, an anthropomorphic entity because it replaces humans and shapes human actions. He objects to the separating lines between humans and technological objects placed by sociologists; he sees only actors who are either human or non-human.[58] Such seemingly animate technological objects, social actors in Latour's view, especially apparent in the work of A-Life and the field of sociable robotics mentioned earlier, challenge modernity's human-machine distinctions. Lucy Suchman discusses A-Life within the wider philosophical problem of human-machine distinction and the autonomy of the machine:

> *Having systematically established the division of humans and machines, technological imaginaries now evidence worry that once separated from us machines are rendered lifeless.*[59]

She further explains that the insistence on the human-machine distinction within the modern tradition drives the prospect of constructing autonomous anthropomorphic machines in order to be humanised, i.e. 'to be made like us - in order that we can be reunited with them'.[60] However, as Suchman points out, although aiming at the opposite, the actual production of intelligent robotic machines lies in the modern tradition of the post-enlightenment era which regards separation and autonomy rather than relation as characteristics of humanity.[61]

Bruce Mazlish locates this distinction and need for unification in a historical framework described by three discontinuities - artificial distinctions - in the western intellectual civilisation, which were overcome by three great scientists of the past: the first, which placed man in a dominant separate position over the cosmos was overcome by Copernicus, the second, which separated man from the rest of the animal kingdom, was overcome by Darwin, and the third placed man over the subconscious (overcome by Freud).[62] Mazlish explains that, as Copernicus, Darwin and Freud refuted these presumed discontinuities, now it is necessary to subvert the *fourth discontinuity*, that is, the fallacy that humans are different from the machines they make.[63] Examining the human-technology relationships through Darwinian theory, Mazlish argues that human nature includes both animal and machinic qualities, because tools and machines are inseparable from human evolution.[64] Human nature, then, is an evolving identity unfolding in terms of culture, our 'second nature', expressed in the form of *prosthetic* devices, either tools or machines - a subject elaborated by Freud, who called man a 'prosthetic god', and Norbert Wiener, who talked about devices like radars, jet engines and propellers in terms of prosthetic human or animal organs.[65]

Having said that, it now becomes clearer that there are cultural factors driving the conception of digitally-driven architectural structures, not unrelated to the philosophical discourse and practices of A-Life and marginal-object production. The machinic yet biomorphic and naturalised behaviour of these structures and the reference to them as if they are social entities, allowed me to place them within the discourse and practices of marginal objects in the history of A-Life. Such objects were understood as challengers of human-machine discontinuity as well as possible means to reunite humans with objects and machines. Similarly, digitally-driven kinetic architecture could also be regarded as a machine, an artificial marginal object, 'trying' to acquire life, to become living organism in order to subvert Mazlish's fourth discontinuity. Its animate, seemingly human features, - motion, pro-activity and responsiveness - turn it into a prosthetic extension of humans and human functions (perception, action, intelligence), echoing the way Oosterhuis has conceptualised his E-motive House project: 'a social semi-independent extension of the human bodies of the inhabitants.'[66]

Conclusions

By analysing the concept of the marginal object, its historical framework and the socio-cultural factors driving its construction, I have built a conceptual framework in order to support my view regarding the reasons behind the design of digitally-driven kinetic architecture. I have argued that these designs are led by a wider socio-cultural (and perhaps psychological) drive which can be observed in different artificial-life objects and 'living' machines. If the task of A-Life practices is to subvert the human-machine discontinuity pointed out by Suchman and Mazlish, then the design and construction of 'living' digitally-driven structures, like the E-motive house, the Muscle Tower II, or dECOi's Hyposurface must be part of this task to 'humanise' the machine-architecture, to undermine the nature-artifice boundary. Digitally-driven kinetic structures should not only be considered as functional objects but should also be seen as quasi-objects, which, in the context of Latour's nature-culture separatism critique, are constructed to challenge and reunite subject and object, human and machine. Yet, it should be clarified here that this bonding is not literal: it does not mean an actual unity between human and structure. It is only a conceptual interpretation of the possibility for prosthetic relations that such anthropomorphic structures generate due to the illusory perception that they are 'alive' entities. To achieve such a bonding, that is, an actual experience of unity between the human and the structure, one should look into other, more intimate devices, practices and discourses within fields such as human-machine interaction and the cyborg metaphor.

What then is the impact of the above observations and this alternative way of understanding digitally-driven structures? Are these observations obstacles to their actual functional potential and aim? Do designers have to change their attitude towards their conception and design? I think the answer to these questions is twofold.

On the one hand, designing and constructing such structures is indeed an important experiment for the evaluation of their behaviour, functional capacities and potential. Unlike closed deterministic machines, these 'naturalised' machines seem to open possibilities. They can be considered to be 'virtual machines', that is, architecture with undeveloped potential, awaiting the activation of possible functions and uses not yet actualised.[67]

On the other hand, we should not look at these structures as fanciful expressions of anthropomorphic qualities, which could obscure their real functional potential. Since functional flexibility and environmental adaptation are, and should be, the main reasons for designing and building such structures - otherwise they should not be considered architecture - it is important to acknowledge that sometimes simple approaches may lead to significant results. Flexibility and adaptation is not only a matter of mechanical and digitally-driven motion of structures but it can be a property of inert structures. Buildings can alter their environment and spatial organisation through the use of mobile elements (moving partitions, retractable roofs, kinetic panels or louvers on 'smart' building skins) which can achieve, with rather discrete motions, extensive changes in function and overall performance. For instance, think of the way that small motions of 'smart' façade louvers can result in significant changes in the building's environmental behaviour and interior conditions.

There is no space here for further elaboration of these ideas. However, the contribution of this paper to the discussion on digitally-driven structures is that it raises questions about the criteria on which these designs are conceptualised and implemented. Although most digitally-driven structures are academic research projects with minimal professional and commercial application, in my view, their discussion through the conceptual framework presented in this paper is crucial for evaluating and anticipating the very possibility of their further exploration and implementation. In other words, by acknowledging the socio-cultural aspects of this kind of architecture, the designers of such structures are confronted with the demand to debate their status and significance, as well as re-examine the related concepts and practices.

Notes

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2. Konstantinos Oungrinis, *Structural Morphology and Kinetic Structures in Tranformable Spaces* (Thessaloniki: Unpublished Doctoral Dissertation Dept of Architecture A.U.TH., 2009), pp. 43-49, 36-37.
3. Ibid., pp. 136-65.
4. See: Tony Robbin, *Engineering a new Architecture* (New Haven CT: Yale University Press, 1996), p. 38.
5. Konstantinos Oungrinis, *Transformations: Paradigms for Designing Transformable Spaces* (Cambridge: Harvard University Graduate School of Design, 2006), p. 7. For instance, in the work of Archigram nomadic kinetic structures are iconographic expressions of a modern technologically-enhanced lifestyle.
6. For instance, the Adaptive Home, the PlaceLab and the MavHome are some of the most representative examples of intelligent environments built to develop techniques - through information processing, memory, recognition and learning mechanisms, and decision-making capacities - to anticipate and adapt to personalised human desires and needs. See: *Intelligent Environments: Methods, Algorithms and Applications*, ed. by Dorothy Monekosso, Remagnino Paolo & Kuno Yoshinori (London: Springer, 2008).
7. Michael Fox, 'Beyond Kinetic', *Kinetic Design Group*, <http://kdg.mit.edu/Pdf/Beyond.pdf> [accessed 30 January 2006].
8. Antonino Saggio, 'How', in Francesco De Luca & Marco Nardini (eds), *Behind the Scenes: Avant-Garde Techniques in Contemporary Design* (Basel: Birkhauser, 2002), pp. 5-7.
9. For a review of environmentally-responsive buildings with kinetic smart building skins see: C.C. Sullivan, 'Robo Buildings: Pursuing the Interactive Envelope', *Architectural Record*, 194, 4 (April 2006), 148-156.
10. *MuscleRoom*, <http://www.protospace.bk.tudelft.nl/live/binaries/7c13c533-6f9b-4f0b-a113-0c0ad9aaa37a/doc/index.html> [accessed 23 April 2008].
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12. Oungrinis, *Structural Morphology*, pp. 359-360.
13. Hyperbody Research Group website, TUDelft, <http://www.tudelft.nl/live/pagina.jsp?id=2e0eef38-3970-4fc0-8e0b-1ce04928c500&lang=nl> [accessed 17 March 2006].
14. See the Responsive Environments projects from 2001 to 2004: *AADRL.net*, <http://www.aaschool.ac.uk/aadrl>.
15. *Hyposurface*, <http://www.hyposurface.org>.
16. Kas Oosterhuis, 'E-motive House', *ONL 2002*, <http://www.oosterhuis.nl/quickstart/index.php?id=348> [accessed 24 February 2008].
17. Ibid.
18. Kas Oosterhuis, *Hyperbodies: Towards an E-motive Architecture* (Basel: Birkhäuser, 2003), p. 54.
19. Nimish Biloria and Kas Oosterhuis, 'Envisioning the Responsive Milieu: An Investigation into Aspects of Ambient Intelligence, Human Machine Symbiosis and Ubiquitous Computing for Developing a Generic Real-Time Interactive Spatial Prototype', *CAADRIA '05 Proceedings* (New Delhi, 2005), 430.
20. Muscle Tower II: An interactive and Kinetic Tower, TUDelft, <http://www.tudelft.nl/live/pagina.jsp?id=42d12e00-5d78-42d1-afe0-262352934565-&lang=en> [accessed 17 March 2005].
21. Hans Hubers, e-mail to the author, February 10, 2009.

22. <http://www.thegreatesthits.net/hyperbody/mov> [accessed 11 October 2009].
23. There is a significant amount of research experiments in psychophysics, which study the perception of animacy in inanimate objects. See: Fritz Heider and Mary-Ann Simmel, ‘An Experimental Study of Apparent Behavior’, *American Journal of Psychology*, 57 (1944), 243-59, and Brian Scholl and Patrice Tremoulet, ‘Perceptual Causality and Animacy’, *Trends in Cognitive Science*, 4 (2000), 299-309.
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26. Cybernetics, defined by its founder Norbert Wiener as the science of control and communication in the animal and machine, attempted to conceive of organic and inorganic systems as information exchange devices, systems able to adapt and adjust to their environment on the basis of the flow and control of information - a unit common to both.
27. Hadas Steiner, *Beyond Archigram: The Structure of Circulation* (London; New York: Routledge, 2009), pp. 13-20.
28. The term and its definition appear in their Archigram 8 periodical (Steiner, op. cit., p. 166).
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34. Maria-Luisa Palumbo, *New Wombs: Electronic Bodies and Architectural Disorders* (Basel: Birkhauser, 2000), p. 76.
35. Sherry Turkle, *The Second Self: Computers and the Human Spirit* (2nd ed.) (London; Cambridge, Mass: The MIT Press, 2005), pp. 34-35.
36. See Sylvia Berryman, ‘The Imitation of Life in Ancient Greek Philosophy’, in *Genesis Redoux: Essays in the History and Philosophy of Artificial Life, ed. by Jessica Riskin* (Chicago; London: The University of Chicago Press, 2007), pp. 35-45.
37. See: Jessica Riskin, ‘Eighteenth-Century Wetware’, *Representations*, 83 (2003), 99.
38. Jessica Riskin, ‘The Defecating Duck, or, the Ambiguous Origins of Artificial Life’, *Critical Inquiry*, 29, 4 (2003), 601-33.
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40. Darren Tofts, ‘On Mutability’, in *Prefiguring Cyberculture*, p. 3.
41. Katherine Hayles, *How we Became Posthuman: Virtual Bodies in Cybernetics, Literature, and Informatics* (Chicago: The University of Chicago Press, 1999), pp. 62-65.
42. Margaret Boden, ‘Introduction’, in *The Philosophy of Artificial Intelligence* (Oxford; New York: Oxford University Press, 1990), p. 7.
43. Sherry Turkle, *Life on the Screen: Identity in the age of the Internet* (London: Weidenfeld & Nicolson, 1995), pp. 133-36.
44. Turkle, *The Second Self*, pp. 282-83; *Life on the Screen*, p. 84. The first computers and smart devices of the 1970s would challenge people’s psychologi-

cal reactions because of their opaqueness, real-time reactivity and unpredictable behaviour. Logic and intelligence, which have always been unique human attributes, were now attributed to machines, thus challenging human-machine boundaries. See: Turkle, *The Second Self*, p. 248.

45. Keller, op. cit., pp. 63-64; Christopher Langton, 'Artificial Life' in *Artificial Life: The Proceedings of an Interdisciplinary Workshop on the Synthesis and Simulation of Living Systems* (Redwood City: Addison-Wesley, 1989).
46. Hayles, op. cit., p. 224.
47. See: Rodney Brooks, *Cambrian Intelligence: The early History of the new AI* (Cambridge Mass.: The MIT Press, 1999). Robotics research in A-Life, for instance, has produced anthropomorphic artefacts, such as Cynthia Breazeal's Kismet, able to develop social and emotional relations with people. See: Cynthia Breazeal, *Sociable Machines: Expressive Social Exchange between Robots and People*, Doctor of Science Thesis (MIT, May 2000).
48. Turkle, *Life on the Screen*, p. 84.
49. Warren Sack, 'Artificial Human Nature', *Design Issues*, 13 (1997), 64.
50. Bruce Mazlish, 'The Man-Machine and Artificial Intelligence', *Stanford Electronic Humanities Review*, 1995, <http://www.stanford.edu/group/SHR/4-2/text/mazlish.html> [accessed 4 July 2008].
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52. Bruno Latour, *We Have Never Been Modern*, trans. by Catherine Porter (Cambridge Mass.: Harvard University Press, 1993).
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57. Jim Johnson (Bruno Latour), 'Mixing Humans and Nonhumans Together: The Sociology of a Door-Closer', *Social Problems*, 35, 3 (1998), 298-310.
58. Ibid., 303.
59. Lucy Suchman, *Human-Machine Reconfigurations: Plans and Situated Actions* (2nd ed.) (Cambridge: Cambridge University Press, 2007), p. 213.
60. Ibid., p. 214.
61. Ibid., pp. 213-14. Criticising robotic artefacts like Kismet, Suchman argues that these machines seem to be working autonomously and pro-actively because of the ways they are reproduced and depicted in media, thus restating traditional assumptions about human nature as autonomous (Ibid., p. 238).
62. Mazlish, here, follows Freud who, in his 8th lecture of the *Introductory Lectures to Psychoanalysis* given at the University of Vienna between 1915 and 1917, proposed a place for himself among Copernicus and Darwin. See: Mazlish, op. cit., p. 3.
63. Mazlish, op. cit.
64. Ibid., pp. 8, 216, 233.
65. Ibid., p. 198.
66. Oosterhuis, *Hyperbodies*, p. 55.
67. A rephrase of Alan Turing's 'Universal Machine' proposed in 1936, and understood in terms of Deleuze's concept of the 'virtual', the 'virtual machine', is a functionally underdetermined complex machine, never actualised as the totality of functions of which it is capable. See: Martin Lister et al., *New Media: A Critical Introduction* (London; New York: Routledge, 2003), pp. 360-64

Biography

Sokratis Yiannoudes is an Adjunct Lecturer at the Technical University of Crete, teaching architectural design and digital media. He is a PhD candidate at the National Technical University of Athens exploring the psychological, socio-cultural and functional aspects of kinetic intelligent architecture, parts of which he often presents in international conferences (Intelligent Environments). He holds a Diploma of Architecture (National Technical University of Athens, 1998), a Master of Architecture (University College London, 2000) and a Master of Philosophy (Royal College of Art, 2004). He was awarded for his innovative designs with the L'Architettura Automatica Prize in Bologna and the Keppie Prize in London. He has worked as an architect in London and Athens, where he currently lives and works.

Modulating Territories, Penetrating Boundaries

MarkDavid Hosale and Chris Kievid

Introduction

Commissioned by Festo, the InteractiveWall[1] is an architectural-scale installation work developed for presentation at the Hannover Messe 2009, the world's leading showcase for industrial technology [fig. 1]. The InteractiveWall was a collaboration between Festo, Burkhardt Leitner constructiv, and Hyperbody,[2] as part of the Festo Bionic Learning Network.[3] (See Acknowledgements for a listing of participants and contributors).

Participation in the InteractiveWall project provided Hyperbody with an opportunity to develop an interactive architectural component that transforms the wall from a static backdrop to a key part of a dynamic customisable environment. For Hyperbody the motivation for the development of interactive architecture is a response to the rise in demand of programmable, multi-mediated, and customisable environmental conditions in the digital age. As the paradigm shifts in the international architectural discourse towards the integration of new technologies, materials and performance, investigations into interactive architecture will help transform and revolutionise our social life in the domestic built environment. Inventing entirely new ways of using and designing space incites us to explore new ways of embodying user participation and locality. One of the most effective ways to seek out this exploration is through the development of installations that allow researchers to isolate and explore problems effectively in interactive architectural design.

Related Works

The compelling works of Aegis Hyposurface[4] by dECOi, and Party Wall[5] by nArchitects help illustrate the context in which the concept of interactive walls has been previously explored. Although quite different in their aims and accomplishments, these projects transform and redefine the traditionally understood connotation and transforming identity of a wall when it becomes interactive: passive becomes active, determined becomes indeterminate, material becomes immaterial, permanence becomes temporal, barrier becomes transfuse, and boundary becomes borderless.

Aegis Hyposurface was built upon a framework of pneumatic pistons, springs, and metal plates, all of which were used to deform a programmable façade-like surface.[6] This sensitive wall interacts spatially with its environment by moving its interlocking flexible panels in synchrony in response to various stimuli from the surrounding environment. Projects such as the Hyposurface help explore the impact on participants when encountering a dynamic full-scale architectonic building object. According to the testimony of the project creators, participants experienced the movements of the Hyposurface with a great deal of curiosity and awe.

Just like Aegis Hyposurface, Party Wall manipulates the quality of the space, by creating a variable boundary of an exhibition. In reaction to the presence of participants, the Party Wall dynamically modulates its territorial and spatial qualities by moving portions of horizontal strips of foam that make up the wall. Because the wall is a permeable membrane, visitors on either side are enabled to engage in a reciprocal relationship. As a result of this mediation between changing conditions the wall governs interaction between the participants.

Like the InteractiveWall, each of these works reflects fluctuations within the environment that surround it and alters its expression in response to these changes. However, the varying qualities of movement when comparing these works with the InteractiveWall underscore their difference, for each new method of actuation results in a unique experience of the architectonic object. Also, unlike these works, the InteractiveWall did not confine its behavioural expression to the modality of movement. Rather, the capacity of the InteractiveWall to serve as an interactive structure is also reliant on the expression of state through the combined modalities of movement, light, and sound.[7]

Technical Description

The InteractiveWall is composed of 7 wall components measuring 1.09 meters wide, 0.53 meters deep, and 5.30 meters tall. The basic composition of each element is a frame structure covered by an elastic fabric skin. Contained within each element are all the motors, sensors, lighting, loudspeakers, and interfacing needed to make the element operate. Therefore each element can be considered a self-contained system. Thus the InteractiveWall is a modular system, whereby elements can be readily added or removed, change location, and arranged in any order [fig. 2].

Each element of the InteractiveWall can move independently in a fluid-like fashion under computer control. The kinetic behaviour of the InteractiveWall is based on a proprietary technology used in Festo's factory automation known as the Fin Ray Effect, developed by Leif Kniese of EvoLogics.[8] Derived from the functional anatomy of a fish's fin, the Fin Ray structure consists of two alternating tension and pressure sides flexibly connected by rigid ribs. When one of the flexible sides is subjected to pressure the Fin Ray structure bends in the direction opposed to the force applied, exhibiting a high degree of movement with minimal effort. In the InteractiveWall, each element is composed of longer flexible supports (made out of a carbon-composite material) and stiff interior supports (made from aluminium tubing). Pushing or pulling near its base will lengthen one side of a Fin Ray element, causing the structure to curve toward the direction force. In the InteractiveWall element the shape of a Fin Ray element is controlled using a pair of DNCE-32-400 electronic cylinders, driven by EMMS-40-M-TMB servo motors (provided by Festo AG & Co. KG), which pushes and pulls on one side of the wall element in order to dynamically achieve a desired form.Within each wall element is a Festo CMMP-AS motor controller, which directly controls the position of the servo motors (and thereby the pistons). In order to unify the communications and control, Hyperbody interfaced with the CMMP-AS using custom circuitry built around Arduino,[9] an open-source electronics prototyping platform [fig. 3].

In addition to proving an interface to the Festo hardware, the custom circuitry was designed to control lights and read sensor data in each InteractiveWall element. Each element has 48 channels of LED light control. The lights are embedded behind the skin, with 24 channels of LED light distributed non-linearly on each side. The distribution of the 48 light channels was made possible via an *LED Painter* circuit based on the TLC5940 IC PWM driver, sold off-the-shelf by Brilldea.[10]

For sensing, MaxBotix *MaxSonar*[11] motion sensors capable of detecting distance were employed. Each InteractiveWall element has two sensors, one for each side. In the software, sensors were combined to create an image of the sensor space, which was used to interpret user presence around the InteractiveWall.

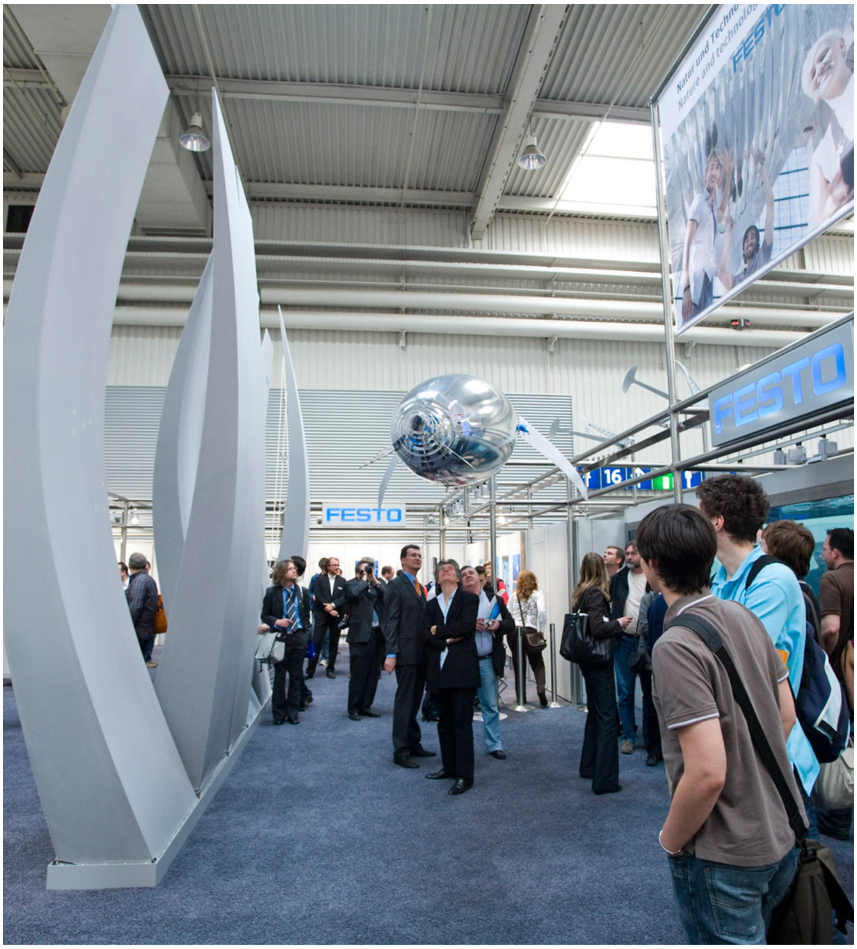


Fig. 1

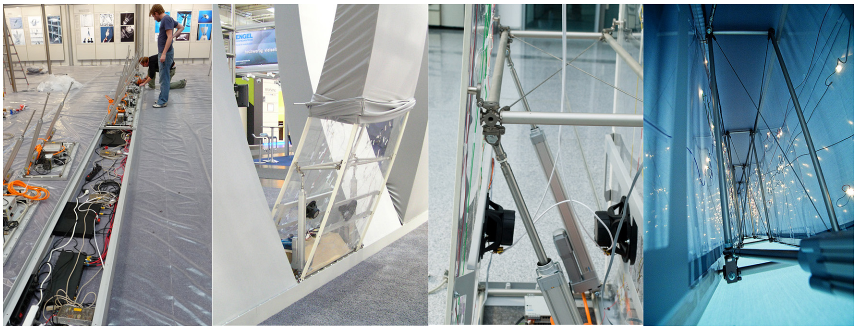


Fig. 2

Fig. 1: The InteractiveWall at the Hannover Messe. Copyright Festo AG & Co. KG, photos Walter Fogel.

Fig. 2: The exposed frame of the InteractiveWall, showing the interior pistons and electronics infrastructure. Copyright [Hyperbody and] Festo AG & Co. KG, photos Walter Fogel

Sound production in the InteractiveWall was developed using a software package called Ableton Live.[12] Each InteractiveWall element has an independent audio channel distributed by a multichannel audio interface, embedded in the base of the composite of InteractiveWall elements.

The central point of the various modalities of the InteractiveWall elements was a custom-control software, designed in a software development toolkit called Max/MSP/Jitter.[13] Through the interface the various systems of the InteractiveWall could be monitored, sensors could be calibrated and filtered, and the behaviour of the system could be controlled [fig. 4].

Behaviour

As a multimodal interactive system the InteractiveWall consists of a layering of the modalities of movement, light, and sound. The development of the general behaviour of the InteractiveWall was inspired by the phenomenon of emergent synchrony as described in the book *Sync: the Emerging Science of Spontaneous Order* by Steven Strogatz[14] and in his talk on TED, *Why things sync up*.[15] According to Strogatz, spontaneous synchronous order (which Strogratz describes as *sync*) is an observable characteristic found throughout nature in systems ranging from physical phenomenon to complex social behaviours. In his talk on TED, Strogatz asserts that the phenomenon of *sync* is guided by a simple set of four rules:

1. Individual elements are only aware of their nearest neighbours.
2. The elements have a tendency to line-up in relation to each other.
3. While the elements follow each other, they are attracted at a distance (either a spatial distance, a time distance, or both).
4. Response to stimulus. The agents in a sync system respond as a single entity, rather than as individuals, when their swarm structure is disrupted (for example when attacked by a predator).

One way Strogatz illustrates the phenomenon of *sync* in his book is through the behaviour of the firefly. Fireflies have a tendency to synchronise their flashing tails whenever they are near each other. Through the cumulative effect of their flashing tails complex patterns emerge out of a simple localised behaviour of emergent sync. Although they are fairly simple animals, the fireflies are incredibly able to maintain this sync behaviour even when they are swarming by the thousands.

The behaviour of the InteractiveWall can be described in terms of the four rules of sync, as described above. While the primary synchronous behaviour of the firefly is flashing light, the baseline behaviour of the InteractiveWall is expressed in movement, as illustrated in Figure 5. As shown in step 1, in its resting state the 7 InteractiveWall elements are aligned in a row on the showroom floor of an exhibition. Step 2 illustrates how approaching participants disrupt the InteractiveWall elements, which react to the participants by bending away from them in response to their presence. The bending behaviour is a local response, with each element bending independently based on the distance of the participant from the node. The elements of the InteractiveWall bend independently of neighbouring elements in response to the presence of a participant. Although responsively independent, the InteractiveWall elements also synchronise by constantly readjusting their positions in order to align with the position of their nearest neighbours. The synchronous behaviour between the elements of the InteractiveWall conflicts directly with the asynchronous behaviour produced by the response to a participant. The result is a series of complex wave patterns that propagate through the InteractiveWall as a whole; this is illustrated in the three phases of step 3. If the wall is left alone it will ultimately come to a resting state as shown in step 3c.

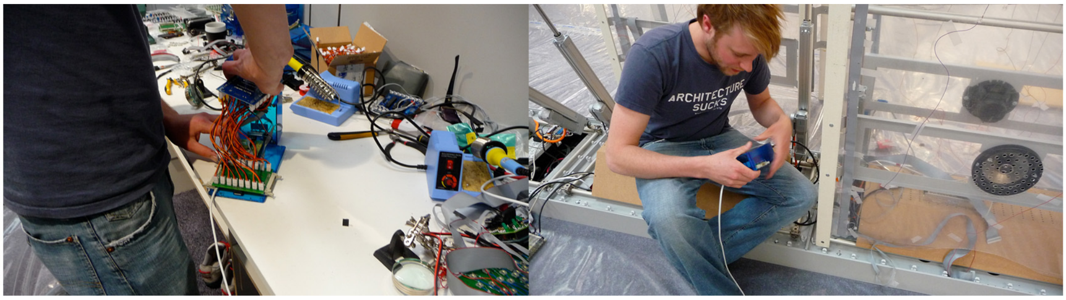
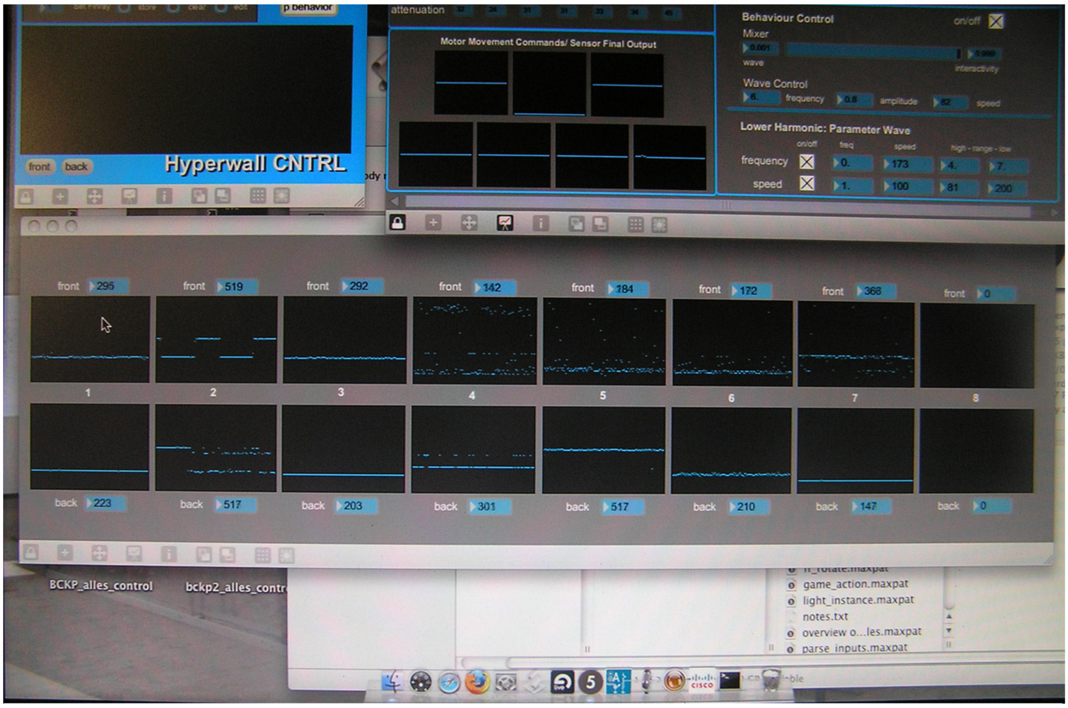


Fig. 3



Behaviour Control on/off ☒
Mixer
wave 0.001
interactivity 0.999
Wave Control
6. frequency
0.8 amplitude
82 speed
Lower Harmonic: Parameter Wave

	on/off	freq	speed	high - range - low	
frequency	☒	0.	173	4.	7.
speed	☒	1.	100	81	200

front 295
front 519
front 292
front 142
front 184
front 172
front 366
front 0

back 223
back 517
back 203
back 301
back 517
back 210
back 147
back 0

Fig. 4

Fig. 5. 1. 2. 3a. 3b. 3c.

Fig. 3: Assembly of one of the Arduino-based control boxes developed for each InteractiveWall element.

Fig. 4: The custom control software for the InteractiveWall, running on a MacBook Pro during the set-up for the exhibition at the Hannover Messe.

Fig. 5: 1.The seven elements of the InteractiveWall; 2.Participants approach the wall, stimulating movement in the wall elements; 3.Cumulative wave patterns emerge in the body of the wall, resulting from inter-element synchronous behaviour conflicting with the asynchronous input.

To express the modality of light, the skin of each component of the InteractiveWall is covered by a unique, irregular distribution of dynamically controlled LEDs [fig. 6]. The LED skin changes in response to the motion of the body of the InteractiveWall component by forming more agitated patterns when a component is moving outwards, and more tranquil patterns when the element is centred. The sum of the behaviour unfolding on LEDs on the individual InteractiveWall components forms an emergent, highly reactive pattern of light that glides across the body of the InteractiveWall as a whole.

As with the light and movement patterns, the modality of sound expresses the localised condition of an InteractiveWall component. In this case sound changes state as an expression of the local sync of a particular InteractiveWall component in relation to its neighbouring components. The amount of sync is determined via a ratio based on the alignment of an individual component in relation to its neighbours. Moments of synchronicity are represented by calmer, lower pitched sounds, while asynchronous behaviour results in more intense sound. The propagation of the sound from high to low intensity is varied throughout the InteractiveWall, transforming each node into a member of a choir that sings the composite state of the InteractiveWall as a complex pattern of oscillating chords.

As described above, users interact with the InteractiveWall by perturbing the synchronous qualities of the InteractiveWall. Via the sonar sensors embedded in the wall, both sides of the InteractiveWall are responsive to approaching participants. Therefore, the InteractiveWall often must negotiate between two participants standing on both sides of a component simultaneously. The InteractiveWall resolves this situation by favouring the participant who is closest to the wall and responding only to that participant. This gives rise to an emergent game-like quality in the InteractiveWall components [fig. 7]. The InteractiveWall has a tendency to move away from the participant closest to a component. As a result the closest participant is rewarded by the component by being sheltered by the arc of the component's curved form. Meanwhile the participant furthest away from a component becomes even more repelled, because the component is pushing them farther away from the structure.

Although connected, the physical movements of InteractiveWall components, the light patterns, and the sound behaviour change independently, reacting at varying rates, expressing the qualities of the InteractiveWall's behaviour in a unique manner. The combination of these components contributes to the living system as scaled and modulated expressions of the synchronous and game-like systems described above.

Results & Evaluation

The primary goal of the development of the InteractiveWall was to develop a compelling exhibit for Festo at the Hannover Messe. However, Hyperbody attempted to seize this opportunity to also evaluate the impact and performance of the work. In order to investigate the performance of the InteractiveWall the public interactions with the prototype during the Hannover Messe were recorded. The direct observation and analysis of recorded video provided a general starting point for understanding of how participants approach and interact with the installation. But, because of the formal circumstances of Hannover Messe it was not possible to execute any user-based surveys, so evaluations were based on subjective observation alone.

Besides the formal limitations and our lack of user-based surveys, other factors confounded our results mostly due to the large number of visitors coming to see the exhibit in the Festo booth. Specifically the high rate of visitors and the other activities happening in the Festo booth made it difficult to recognise the direct impact of the InteractiveWall on the participants, specifically who was willing to

Fig. 6a b

Fig. 7

Fig. 6: a.Front view of the InteractiveWall (long shutter speed). b.The InteractiveWall by night, showing the irregular distribution of lights on the skin. Copyright Festo AG & Co. KG, photos Walter Fogel.

Fig. 7: The responsive behaviour of the InteractiveWall leads to active participant engagement. Copyright Festo AG & Co. KG, photos Walter Fogel.

'play', and who wasn't; and whether or not a participant could recognise another user's involvement in the 'play' of the work.

Despite these complications, there were moments of slower activity and clear engagement on behalf of visitors' participation with the InteractiveWall. Finally, the context of the Messe provided some insight into how well such a system performs in a somewhat real-world environment, full of distractions and other participants, and context could not be readily controlled.

Through these observations some initial comments can be made about the impact of the work (at least in this context) and some potential areas for future improvements. As might be expected, many participants seem clearly drawn to the 1-to-1 layers of interaction in the system. We gather this because the movement was difficult to interpret; many participants were initially drawn to the light, after which they might recognise interactivity in the movement, assuming that other participants were not disturbing the InteractiveWall from the other side. Also, participants seemed (logically) more engaged with the work during quieter moments of the exhibition. Due to the high volume of visitors and surrounding exhibitions, the sound was often difficult to hear as well. But in quieter moments participants were able to hear the sounds and experience all of the modalities of the work. This, in correlation with the increased engagement of the user, could be seen as an indication of the increased interest of the participants when they experienced of all of the modalities of the work.

Applicability

The Dynamic Sound Barrier-project proposal by our partner from practice, ONL [Oosterhuis_Lénárd],[16] came forth as an ambitious and groundbreaking initiative to extrapolate the technology employed by the InteractiveWall and apply it within the real world of design and construction. Working within the boundaries to stylise and optimise a building form for maximum noise reduction and aesthetics, the Dynamic Sound Barrier shows that applied technology can liberate architectural form in a way that makes it more efficient and viable.

Inspiration for the development of the Dynamic Sound Barrier rose out of the desire to mediate between the conflicting needs addressed by conventional acoustic barriers to limit the intrusion of high-noise pollutants, such as train tracks and large highways, while eliminating the resulting fragmented territory created by the introduction of the barrier in its context. As a dynamic structure the Dynamic Sound Barrier mediates between the conflicting programs of noise reduction and open territory by modulating between two states. When no trains are nearby, the Dynamic Sound Barrier lies in a resting state, close to the ground, exposing the landscape around it. When a train approaches the Dynamic Sound Barrier comes alive by standing erect, obscuring the noise from the train, while only momentarily obscuring the landscape around it [fig. 8].

Like the InteractiveWall, the Dynamic Sound Barrier is composed of a population of architectural components that are given a dynamic behaviour in real time. Like in the InteractiveWall, the combination of sensors and actuators embedded in the proposed structure would enable the components to interact with surrounding components in a self-organised manner. The design strategy of the employment of dynamic components provides for a high standard of flexibility for the design. Each component is adaptable and responds in accordance with the noise-cancellation and aesthetic requirements. The construct becomes a lean and flexible barrier that only rises when its noise-nuisance function requires it, while the elegant movement of the Dynamic Sound Barrier exhibits unique and compelling architectural qualities. Therefore, in addition to functional noise reduction, the Dynamic Sound Barrier

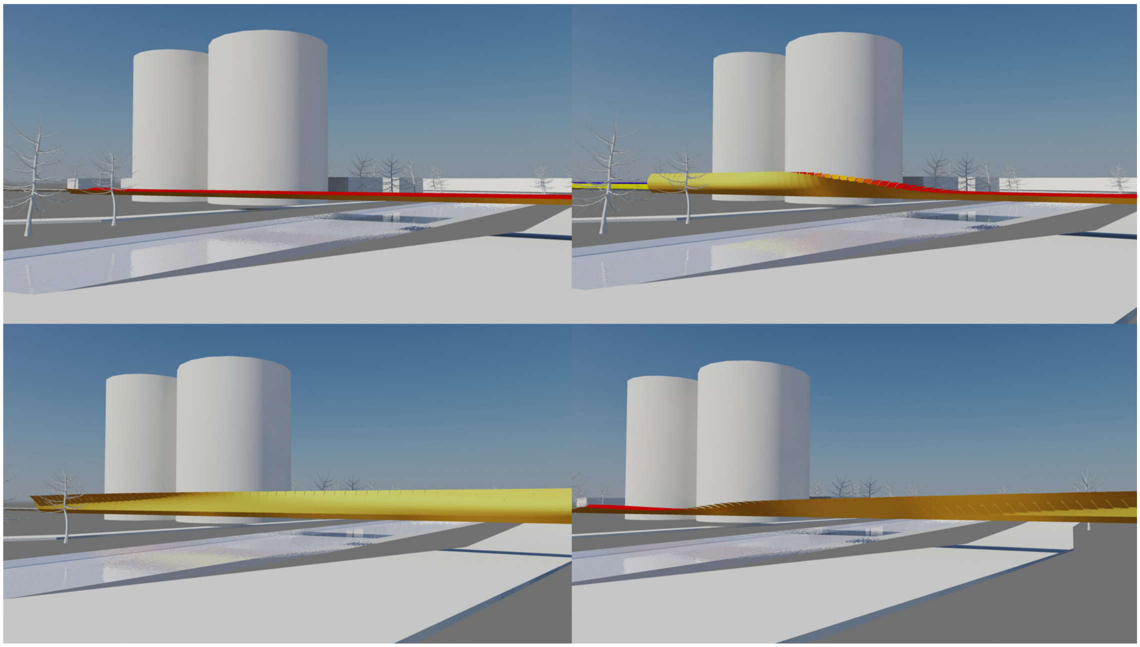


Fig. 8a

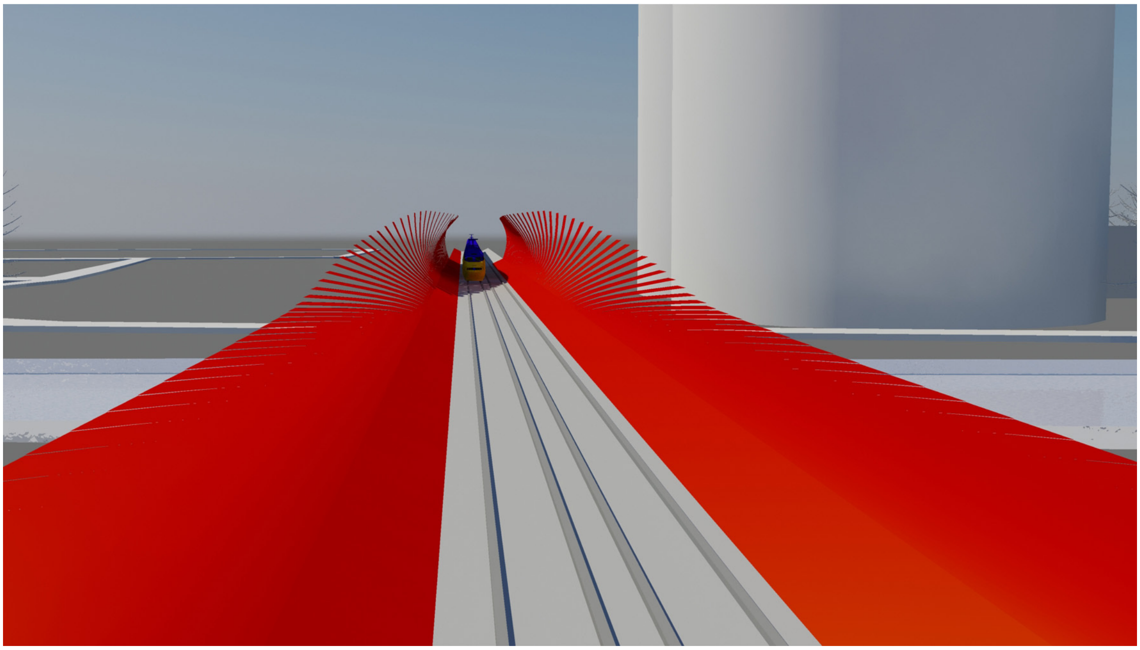


Fig. 8b

Fig. 8: a. the Dynamic Sound Barrier reconfiguring itself to cover the noise from the flow of passing traffic; b. The Dynamic Sound Barrier comes alive by standing erect, obscuring the noise from the train. Renderings ONL [Oosterhuis_Lénárd.

provides an aesthetic addition to the natural environment as well.

The proliferation of emerging interactive architectural projects in the urban environment, such as the Dynamic Sound Barrier, results in a transformation of the built environment.[17] The implied cultural implementations will challenge architecture's traditional identity revolutionising and reinventing our social spaces from static to dynamic.[18] In opposition to traditional architecture the design essence of interactive architectural objects lies not only in their physicality, but also in their behaviour, as both are deeply intertwined. As Michael Fox and Milles Kemp acknowledge in their recent publication Interactive Architecture: '[…] we may no longer ask "What is that building?," or "How was it made?," but rather, "What does that building do?"'.[19]

In order to create successful architectural spaces of this kind, the architectural discipline should not merely focus on designing spatial and behavioural expressions. There is a growing need for guidelines for developing and building spaces and objects capable of dynamic and interactive architectural performance. As the Dynamic Sound Barrier project illustrates, a noise ordinance in the Dutch technical building regulations[20] demands for calculations for peak decibel levels to determine the noise pollution. This is a serious bottleneck in the implementation of a dynamic acoustic structure that only rises when its noise-cancellation properties are required.

Although many government authorities have been working in a 'performance-based building' regulatory environment as a means of improving innovation in building and construction industry,[21] to this date specifications, prescriptive codes, regulations and standards are not currently adaptable to the evaluation of dynamic building objects. In order to better serve dynamic architectural innovations, the view of architectural 'performance' should be expanded and embrace the renewed engagement with architecture as a performing body that establishes relationships between environment and participant.[22] A creative approach to responding to the current requirements related to legislation on building design provides designers a fresh opportunity for reformulating and imposing new regulations. In leading the conception and implementation of the new legislation, researchers and practitioners should play an active role, as this role for 'designing' legislation is as much a design task as any other. If experts in interactive architecture do not take on this task, it is doubtful that non-experts in the planning community will.

Conclusion

The InteractiveWall and Dynamic Sound Barrier help illustrate, in a very literal sense, the definition of penetrating boundaries and modulating territories. In addition, these projects demonstrate a process whereby interactive architectural explorations could be brought to the next level, and start addressing how they can be implemented in real-world contexts. As architecture becomes responsive and interactive, participants can influence its behaviour. In this sense architecture follows a general development in society towards participation, personalisation and customisation, which follows the evolution of contemporary mundane technologies. While much focus in the discourse of interactive architecture has been on experimentation through installations, it is perhaps time to start evaluating these experiments and translating them into real-world projects that will better meet future societal needs.

To design a territory that is changing and adaptive is to design an architecture that is interactive, spontaneous and alive. This is a notion closely linked to Gordon Pask's envisioned perception of architecture as dynamic systems consisting of both buildings and their inhabitants. As Gordon Pask writes: 'Architects are required to design dynamic rather than static entities. Clearly the human part of the system is dynamic. But it is equally true that the structural part must be imagined as continually regulating its human inhabitants'.[23] In this architectural paradigm new design methods and concepts lead to changes in the design process and the role of the architect. As Kas Oosterhuis puts it, 'The architect in society today is a well-trained hyperconscious idiot savant. Today's architect is an information architect, able to act intuitively and to process rationally at the same time'.[24]

While the characteristics of the InteractiveWall and Dynamic Sound Barrier are similar, they have very different aims. The InteractiveWall exhibits a particularly emotive quality that engages participants in a game-like play. On the other hand, the Dynamic Sound Barrier transforms what would otherwise be a static boundary into a living landscape, reconfiguring itself to cover the noise from the flow of passing traffic while avoiding being a static barrier that permanently pollutes the horizon. These differences underscore the flexibility of interactive architectural design in changing contexts.

Festo's commission to develop the interactive design for the InteractiveWall presented at the Hannover Messe industrial trade-fair provided Hyperbody with an architectural-scale prototype for the exploration of interactive architecture. Although the phase of the project described in this article has come to an end, with the full support from Festo, the development on the InteractiveWall will continue. In particular, Hyperbody is planning to continue exhibiting the current version of the wall at different events and making improvements along the way. In doing so, we gain invaluable knowledge on how to develop optimised systems, cascading these improvements to future projects and speeding up future developments. Among the improvements considered will be better sensing and actuating technologies, alternative spatial arrangements and form factors, high resolution flexible displays, and the implementation of embedded distributed computing systems.

Acknowledgements

InteractiveWall copyright Festo AG & Co. KG, photos Walter Fogel. Dynamic Acoustic Barrier, Breda 2009, architect ONL (Oosterhuis_Lénárd) bv Rotterdam, rendering by ONL (Oosterhuis_Lénárd) bv. InteractiveWall has been awarded the GOOD DESIGN™ Award 2009.

Project initiator: Dr. Wilfried Stoll, Chairman of the Supervisory Board, Festo AG.

Project managers: Professor Kas Oosterhuis, Chris Kievid, Bernard Sommer, Hyperbody, Faculty of Architecture, Delft University of Technology, The Netherlands.; Michael Daubner, Andreas Dober, Burkhardt Leitner constructiv, Stuttgart, Germany; Markus Fischer, Festo AG & Co. KG, Ostfildern, Germany.

Project team: MarkDavid Hosale, Remko Siemerink, Vera Laszlo, Dieter Vandoren, Hyperbody, Faculty of Architecture, Delft University of Technology, The Netherlands; Robert Glanz, Domenico Farina, Burkhardt Leitner constructiv, Stuttgart, Germany; Gerhard Bettinger, Roland Grau, Uwe Neuhoff, Festo AG & Co. KG, Ostfildern, Germany.

Notes

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Biographies

Dr. MarkDavid Hosale is a media artist and composer with a PhD in Media Arts and Technology from the University of California in Santa Barbara (2008). As an interdisciplinary artist and composer MarkDavid has found that, beyond the common language of new media, the connecting tissue between various art practices and music can be found in narrative - in particular, the kind of narrative that is structured using nonlinear representations of information, time, and space. Nonlinear narrative is an inherent aspect of new media that provides a common baseline whereby media artworks can be evaluated and understood. In addition to non-linear narrative, MarkDavid's interdisciplinary interest in art and music comes from the exploration of the connection between the physical and the virtual world. Whether as part of an installation work or performance work, the virtual spaces he creates are technologically transparent, sophisticated and virtuosic, as well as intuitive to experience and use.

Chris Kievid is a researcher at Hyperbody, a contemporary information-technology driven research and design group at the Faculty of Architecture of the Technical University in Delft. He graduated *cum laude* in architecture at the TU Delft in 2006. His thesis received a nomination for the Dutch Archiprix 2007. As a freelance architect and interaction designer he has worked for the multidisciplinary design office ONL [Oosterhuis_Lénárd] on a variety of innovative projects. As a researcher and project manager at Hyperbody he has been responsible for the development of the design environment for immediate design and engineering: protoSPACE, the project iLite for the travelling road show Philips Transitions II and the InteractiveWall installation for the Hannover Messe. As a coordinator and tutor he is involved with the Hyperbody educational MSc 2 and minor program.

Mediated Windows: The Use of Framing and Transparency in Designing for Presence

Charlie Gullström

Introduction

If - as Le Corbusier once proposed - the history of architecture is the history of windows, what can we learn from the design of mediated windows, walls and spaces that seek to extend our conception of the discipline of architecture?[1]

In 2008, my colleagues and I designed a mediated museum extension for a pilot study in which a Stockholm museum was extended to an archaeological excavation site, allowing visitors to interact and to be guided remotely in real time, through a mediated window, or glass door. [fig. 1] The activities served to explore how a mediated architectural extension can facilitate access to a cultural heritage site by enabling the experience of remote presence, and how such new forms of communication between a museum and its visitors can inform cultural-heritage processes, as part of ongoing research.[2]

Architectural design is conventionally executed by 'brick and mortar', but new building materials are developing every day, some adapted from the field of media and communications. Delimiting the current paper to a specific example from my own design practice, which explores video as a 'building material', I seek to understand how spatial and aesthetic conceptual tools, derived from related visual practices may apply. I therefore outline the significance of windows in architecture and art to establish the relationship between interior and exterior space. Through the concepts of framing and transparency I then explore how windows have been treated in the modern history of architecture, by the likes of Le Corbusier, Mies van der Rohe and Bruno Taut. I give a brief account of the history of glazing and discuss whether the different possibilities available in art and architecture, to represent the passage from indoors to outdoors, are fully taken into account in the design of mediated spaces. This, in turn, allows me to contextualise my chosen design example - the mediated museum extension.

Presence design and presence research

In enabling audiovisual extensions in real time, presence design emerges as a new field, exposing architectural discourse and practice to radical new concerns. It can be argued that throughout history a broad range of practitioners - architects, artists, writers and filmmakers - have already contributed hybrid design artefacts from a juxtaposition of real space and virtual space: mediated spaces.[3] What is new, today, is that it has become possible to populate these architectural extensions; to inhabit them in ways that allow people to interact and collaborate closely; to see and hear each other, in other words: to be present before one another whilst remaining in different locations. Designing for presence therefore implies the design of shared mediated spaces that enable people to collaborate as well as they might, for example, in their conventional workplace, possibly designed by architects.[4]

A large body of research that informs the design of mediated spaces concerns the concept of presence. In presence research, an often referred to definition of (tele-)presence includes a reference to architectural design: 'the use of technology to establish a sense of shared presence or shared space among geographically separated members of a group'.[5] However, presence research is currently a diversified field, spanning media space research, cognitive science, (tele-)presence research, interaction design, ubiquitous computing, second-order cybernetics, and computer-supported collaborative work.[6] With the proposal that its discourse is characterised by the separations of disciplinary boundaries, and that architecture, design and artistic practices are insufficiently represented, I argue for a transdisciplinary design-led approach, where presence research meets architectural design and incorporates tools and strategies derived from related visual practices. This is the background to my proposal that presence design is distinguished as a separate field.

Two centuries of the window as spatial problem

It is, of course, impossible to say how masters of modern architecture, such as Le Corbusier or Mies van der Rohe, would have treated 'a mediated window' as a building material, but we may turn to exemplars in art and architecture to discuss how, for example, concepts such as framing and transparency have been treated previously.

It was in the second of his ten lectures given in Buenos Aires in 1929, that Le Corbusier related the history of architecture as 'the history of windows throughout the ages'.[7] Elaborating on the five points for a 'New Architecture' presented a few years earlier,[8] he proceeded as follows: 'I am going to announce an outrageous fundamental principle: architecture consists of lighted floors. Why? You can easily guess: you do something in a house if there is light; if it is dark, you are sleeping'.[9] Again, this statement provides a connection to the example we presently examine: without light, electricity and transmission, the design fails completely, there is neither activity, nor architectural extension.

Addressing the double nature of modern glass architecture, Kenneth Frampton has pointed at the unresolved contradiction in Le Corbusier's early work, between a machine-like precision of form and finish and the crude means of realising a building. The Villa Savoye near Paris is one example where a rough concrete framing was rendered in stucco to appear seamless.[10]

Frampton has also observed how Mies van der Rohe's work from the 1920s presents the simultaneous capacity of glass to produce complex optical effects and the ineffable (light, shadow, transparency, reflection) while stressing the material presence of a building and glass as a building material. Frampton breaks it all down to a series of polarities which characterise the use of glass: 'tectonic versus stereotomic; still versus agitated; open versus closed; and above all, perhaps, traditional material versus space endlessness'.[11] Where Frampton discusses tectonics, other scholars have distinguished between 'literal and phenomenal' transparency in Le Corbusier's capacity to combine different architectural elements.[12] For Le Corbusier, the elimination of exterior supporting walls permitted a larger surface of glazing and the use of what he called 'window walls' to seal his mechanically-regulated interiors. Acknowledging that not all façades should be glazed, Le Corbusier presented four glazing strategies: the window wall (*le pan de verre*); the ribbon window (*la fenêtre en longeur*); the mixed wall (*le mur mixte*), and non-loadbearing masonry cladding (*le pan de pierre*).

In an essay from 1973, the art historian Carl Nordenfalk, a specialist in early medieval art, presents the window as 'a 2000-year-old space problem in Western art'. He uses well-known examples to sketch how the role of windows changes through the history of visual arts.

Nordenfalk parallels the use of glazing technologies by Le Corbusier and Frank Lloyd Wright with

Fig. 1

Fig. 2

Fig. 1 The mediated window - or glass-door - designed for a mediated museum extension in 2008, when the Museum of National Antiquities in Stockholm was temporarily extended to an archaeological excavation, thus enabling museum visitors to interact remotely with archaeologists and passers-by at the excavation site. Design: Charlie Gullström & Leif Handberg.

Fig. 2 ‘Dining Room in the Country’ by Pierre Bonnard 1913. (The Minneapolis Institute of Fine Arts, Minnesota).

how the French artist Pierre Bonnard treats the interior and the landscape as if it were one space where the 'the passage between outdoors and indoors is free'.[13] His example is Bonnard's 'Room in the country' from 1913, where we may note that the woman is standing outside, but leans into the dining room through the open window. [fig. 2]

While medieval art can fruitfully illustrate the transparent and reflective qualities of windows, Nordenfalk argues that it is only from the beginning of the fifteenth century that a window's capacity to mediate between indoors and outdoors is represented in the arts. His essay brings the role of the spectator to the fore, whereas architectural theory more often treats a window as part of an exterior skin. In the context of mediated windows, a study which focuses 'the representation of an outdoor view seen through an interior' may therefore be considered useful.[14]

Framing and transparency

The relationship between outside and inside is a central theme in both art and architecture, and a mediated window can be compared to earlier glazing technologies that enabled the human eye to establish a unity or extension between one space and another. Accordingly, the mediated window can be considered as an architectural element. To support this claim we need to examine the origins of glazing and the emergence of the window as an architectural element.

As several scholars have observed, the development of glazing technologies goes hand in hand with the implementation of glass as a new building material in architecture.[15] While framing and transparency may be useful concepts in presence design, we are looking at two different ways of achieving transparency. The transparency of a glazed window comes in the form of silicon dioxide - to which soda has been added to facilitate melting of the batch, and lime, as a stabilizer against the adverse effects of water - whereas transparency in the case of the mediated window is achieved by means of cameras, projections and a chosen means of transmission. Richard Lanham has eloquently addressed the concept of transparency, but with reference to hypertext and writing. Adapted to a more general theory of representation, it is of relevance to the mediated window:

> *The textual surface is now a malleable and self-conscious one. All kinds of production decisions have now become authorial ones. The textual surface has become permanently bi-stable. We are always looking first AT it and then THROUGH it, and this oscillation creates a different implied ideal of decorum, both stylistic and behavioural. Look THROUGH a text and you are in the familiar world of the Newtonian interlude, where facts were facts, the world was really 'out there', folks had sincere central selves, and the best writing style dropped from the writer as 'simply and directly as a stone falls to the ground', precisely as Thoreau counselled. Look AT a text, however, and we have deconstructed the Newtonian world into Pirandello's and yearn to 'act naturally'.*[16]

May we refer to a 'mediated window' as an architectural element; a new building material in line with previous glazing technologies which, in the words of Frampton, have contributed to a 'shift from heavy opacity to light translucence [that] had both tectonic and aesthetic ramifications'?[17] Frampton here refers to the double nature of Mies van der Rohe's architecture of the 1920s, where contrasting qualities of different materials become the terms for a 'binary opposition'. He argues that glass required a skeleton frame, hence a strictly tectonic system in order to sustain itself against gravity.[18] From his collaboration with Lilly Reich, in e.g. the 'Exposition de la Mode' in Berlin in 1927, Mies achieved such contrast in creating 'ephemeral semitransparent screens'. Silk textiles were used which, set against the plate glass, as suggested by Frampton 'yielded

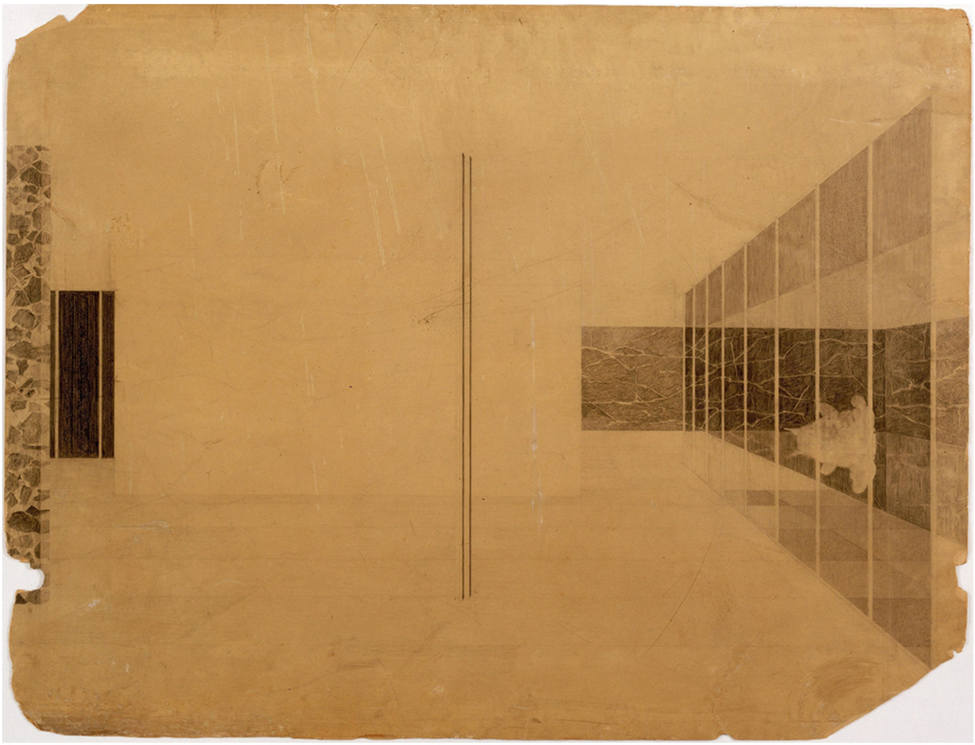

Fig. 3

Fig. 4

Fig. 5

Fig. 3 In 1928, Mies began work on the German pavilion for the 1929 Barcelona International Exposition. In this early interior perspective we see the famous 'Mies column' in the centre and his noticeable concern to render the view through the glass wall into the courtyard, where a reflecting pool and a sculpture of a reclining figure is traced. (Mies van der Rohe archive, Museum of Modern Art, N.Y. © 2010. Digital image Mies van der Rohe/Gift of the Arch./MoMA/Scala).
Fig. 4 Only black-and-white photos exist of Taut's seminal glass pavilion, which was built for the 1914 exhibition, funded by the association of the German glass industry. The fourteen-sided rhombic structure was made of thick glass bricks. (Photo from www.commons.wikimedia.org).
Fig. 5 The interior of Taut's glass pavilion produced a kaleidoscope of colours, with glass-treaded metal staircases leading to the upper interior of the dome. In between the stairs, a seven-tiered cascading waterfall with underwater lighting which, in combination with the sunlight filtered through the structure of concrete and glass, resulted in a cascade of light and colour. (Photo from www.commons.wikimedia.org).

a dematerialized aesthetic plus a constant mirroring of the interplay between the transparent and the translucent'.[19] Frampton discusses Mies's achievement in terms of a paradox, and his phrasing is not altogether alien to our current context: 'on the one hand, the necessity for a frame to support the free-standing silk or glass screens, on the other hand, the ineffable, free-floating, even illusory volumes that these screens engender'.[20]

At the time, Mies himself argued for the freedom which new tools provided to the architect, using similar words that today's designers of mediated spaces are also likely to use: 'These are truly architectural elements forming the basis for a new art of building. They permit us a degree of freedom in the creation of space that we will no longer deny ourselves. Only now can we give shape to space, open it, and link it to the landscape. It now becomes clear once more just what walls and openings are, and floors and ceilings'.[21]

The drawings for Mies's seminal German pavilion of the International Exposition in Barcelona, from 1929, specified wall materials with different reflective capacity as well as subtle kinds of glass. An early interior perspective of the Barcelona pavilion provides an excellent example of Mies's use of transparency and framing. [fig. 3] As formulated by Terence Riley: 'Rather than making the glass look fully transparent, he gives the dark green Tinian marble different shadings behind the wall and to the left and right of it, approximating the visual effect of the screen of gray glass. Even the reflection of the sculpture in the pool is studiously considered'.[22] Mies excels in the articulation of the relationship between inside and outside, but to explore the special properties that allow us to look through glass we need to go further back into the history of glazing.

The emergence of glazing technologies

The themes of reflection and transparency are frequently addressed in architecture, and may be observed in relation to the development of the technologies of glazing, a development which, it can be argued, continues with the use of mediated windows.

Transparent goblets of rock crystal were found in Egypt as early as the First Dynasty in the tomb of Hamaqa, Saqqara and the legend of a glass palace prevails in Jewish and Arabic cultures, for example, through the story of Queen of Sheeba in which Solomon's throne is placed on reflective surface.[23] Little is known of glass-manufacturing in the earliest period, but well before 1450 B.C. several factories in Tell al-Amarna contributed to Egyptian industry during the Bronze Age. Excavations here reveal the existence of industrial structures but there is little evidence, resulting in an ongoing discussion among scholars as to whether the Egyptians made glass from raw material on site or whether glass was imported from the Middle East. Evidence of glass-working in the 11-9th century B.C. is documented in Frattesina, northern Italy and on Rhodes, although archaeologists, to date, have not yet identified any remains of the glass furnaces which produced the high quality glass of this time.[24] By the fourth century B.C. glass was widely manufactured in many parts of the eastern Mediterranean, as a result of glass workers migrating to the west, as well as in Iran. At this time, glass was not yet used as a building material; the mild climate in these countries made it unnecessary to protect interiors, and the function of windows, was rather that of a ventilating opening (c.f. the etymology of the word 'window', denoting 'the wind's eye' in Scandinavian and Old Norse 'vindauga'). The invention of blowing glass in the first century B.C. has been considered as the first step in the development of glass in architecture.[25] Glass-blowing skills were tacitly passed on within Syrian families, who had a basis in Sidon, and managed to export their goods through the Roman Empire.[26]

Fig. 6

Fig. 7

Fig. 8

Fig. 6 ‘The Annunciation’ (The Merode Altarpiece), right panel of the triptych by Robert Campin, a.k.a. The Master of Flémalle, 1425. Just outside his shop window, a mousetrap is on display to attract customers (Metropolitan Museum of Art, New York).

Fig. 7 ‘St. Barbara’ by The Master of Flémalle, 1438 (Museo del Prado, Madrid).

Fig. 8 ‘The wedding of Mars and Venus’. Fresco from the House of Marcus Lucretius Fronto, Late Third Style, ca 30 A.D. Pompeii. See e.g. Clarke (1993:156f) for an interpretation of the motif.

It was the invention of the cylinder method, in the mid-19th century, that made it possible to efficiently produce large sheets of glass. The new method (associated, in England, with the industrialist Lucas Chance) triggered a widespread interest in glass buildings which coincided with a general fascination for science, world travel and exotic plants.[27] Across Europe, museums were established as sites for collection along numerous greenhouses and great exhibitions, such as the Jardin des Plantes (Paris 1833), the Palais des Machines (Paris 1889), the Crystal Palace (London 1852), and the Munich Glass Palace (1834). Accelerated by the iron industry, new architectural expressions were sought for a new type of buildings that the modern and liberal society demanded. As documented, for example by Walter Benjamin, it was from the combination of glass and iron, and the creation of well-lit, large and monumental railway stations, exhibition halls, museums and shopping arcades that the urban bourgeois society developed.[28]

A significant reference, in terms of the modern movement that soon followed, is Bruno Taut's glass pavilion for the Deutsche Werkbund exhibition in Köln 1914. [fig. 4-5] Taut used coloured glass within a concrete skeleton to create a prismatic glass dome that became a landmark at the exhibition. In spite of being destroyed afterwards, the pavilion remains an exemplar of modern architecture and German expressionism.[29] Reyner Banham showed that Taut's pavilion can be closely linked to Paul Scheerbart, a man whose name has fallen into oblivion but with whom Taut and other expressionists defining the period 1910-1925 were close.[30] In effect, Scheerbart is appointed as literary forerunner and instigator of modern glass architecture and his book *Glasarchitektur* appeared in 1914, with a dedication to Taut, praising glass as the building material for a new era: 'Glass brings us the new age. Brick culture does us only harm.'[31] Scheerbart died in 1915, but Taut developed a shared vision of a glass culture in a series of fictive letters known as the 'crystal chain'.[32]

Between World War I and II, Europe was looking for new beginnings and many experiments in the arts, crafts and technology of the late 19th century were bearing fruit. In terms of glazing, Mies van der Rohe, Le Corbusier and Frank Lloyd Wright, along with their many colleagues, were exploring the free passage between indoors and outdoors, confirming a unity between indoors and outdoors which, following Nordenfalk's argument, had taken many centuries to evolve. In the following, I will observe this earlier development in the arts in some detail.

The mousetrap and other design strategies

A survey of how the window is treated in the visual arts provides important insights regarding the technologies of transparency, or design strategies, which this essay wishes to address in the light of more recent developments. Neither the Greeks nor the Romans managed what Robert Campain, the so-called Master of Flémalle, achieved in a row of paintings in the early fifteenth century: a realistically rendered room depicting a window in the back wall through which we get a realistic glimpse of an outdoor world. Nordenfalk points at how a finished mousetrap, placed to attract passers-by to the workshop, has the role of a springboard for our passage from the interior into the outdoor world. [fig. 6]

As Nordenfalk suggests, we may look in vain among the wall paintings of Pompeii and Rome to find an indoor scene that can match those of the Flemish Masters of the early fifteenth century.[33] This now seems so commonplace, why did it take so long?

The simple explanation is that the representation of three-dimensional space is a more recent development. In fact, medieval representations of indoor scenes indicate very incomplete and vague spaces, where three-dimensionality is suggested only by elevated platforms in the foreground, on

Fig. 9

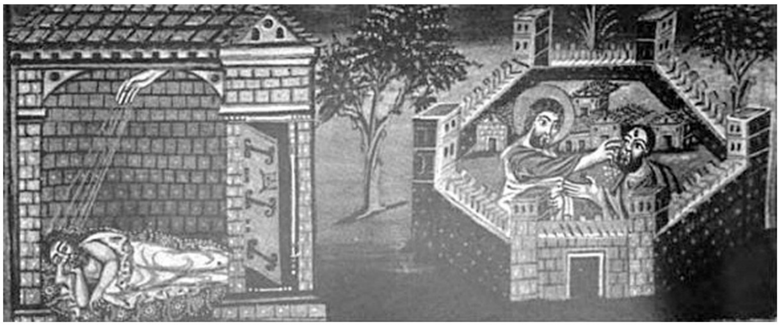

Fig. 10

Fig. 9 ‘Dido on her Funeral Pyre’. Folio 40 recto, Vergilius Vaticanus (Vatican Library, Rome, Vat. Lat. 3225).
Fig. 10 ‘Healing of St. Paul’. 9th century. Detail from miniature in the Vivian Bible, Paris (Bibliothèque Nationale, lat.1. fol.386v).

which immobile figures rest, such as in the House of Marcus Lucretius Fronto in Pompeii. [fig. 7] A second layer of figures can be seen behind the marriage bed, but the space remains elusive as to its actual depth. If the back wall has an open door, it denotes an opening for guests, but does not provide a view out of doors.

Archaeological excavations in Rome have shown that windows often framed a specific view from a living room towards the garden and that open peristyles were of general use in spatial design.[34] Both Vitruvius and Plinius describe rooms where murals provide the illusion of an extension to outdoor scenery or an urban setting. The Pompeian House of the Vettii (fourth Pompeian style) includes such a spatial extension where, in Nordenfalk's words: 'We are clearly invited to look out of the room into an open space. However […], we do not really do so from a simulated interior, but from the real one in which we are dwelling as spectators. Both the openings and the architecture behind them have the character of façade motifs, related to those we know from the Greek and Roman theatres, making the room itself look like an open courtyard'.[35] What Nordenfalk stresses is that, although this is an interior, it is reluctantly depicted as one and modelled on the exteriors of classical theatre design.

Towards the end of the classical period, three strategies develop for the representation of an enclosed space. One is the box-formula, which appears in a manuscript at the end of the fourth century A.D. as part of an illustrated codex featuring major works by the Roman poet Vergilius. [fig. 8] The artist has located the scene where Dido is about to stab herself on her pyre in a closed chamber depicted as a room with sidewalls and in perspective foreshortening. There is a door with a curtain, but it does not offer a view. This, Nordenfalk characterises as typical for how antique space is treated: 'the artist's vision of indoor space fails him. Instead of being set into one of the walls, it cuts the foreshortened sidewall as a loose setting. It is left undecided whether it is a door seen from the outside - an opening into the room - or a door seen from inside and serving as an outlet.[36]

The two other strategies provide exterior views of interior spaces: the bird's-eye view to overview an open space (for example a city) and the depiction of a scene inside a canopy. In both of these, the indoor is as much an open as a closed space: a bird's-eye view of a city will lack a roof and a canopy, walls.

For many centuries these were the main strategies by which an interior could be visualised. The two are used side by side in a miniature of the first Bible of Charles the Bald. [fig. 9] Nordenfalk draws our attention to the building on the left, a real house with walls and a door left open, suggesting a passage between indoors and outdoors. But it is not the door that allows us to look into the space; it is the artificial opening of the front wall which discloses the interior. The canopy-style is here combined with a real house, as a house-canopy which, according to Nordenfalk, provided the medieval pattern from which a realistic interior ultimately emerged.

An intriguing miniature from 984 A.D., by the leading Ottonian painter called 'Master of the Registrum Gregorii', shows the house-canopy strategy reduced into a flat background coulisse, but where the artist nevertheless reintroduces 'a notion of three-dimensional space, by winding a curtain around the shafts of two of the columns […] Like the inquisitive scribe, peeping at him through the hole he has made with his stylus in the curtain'.[37] In accordance with the medieval stratification of parallel layers, the Pope is located in the first, and the furniture and architecture in the second. [fig. 10]

Remarkable as it is with such an explicit depiction of an interior space that includes a spectator from the exterior, Nordenfalk points at the lack of congruence between interior space (contained

Fig. 11

Fig. 12

Fig. 13

Fig. 14

Fig. 11 St. Gregory in his studio, dictating to his curious scribes, from a Registrum Gregorii manuscript (Trier Stadtbibliothek, cod. 802).
Fig. 12 'The Birth of the Virgin' by Pietro Lorenzetti 1342 (Museo dell'Opera del Duomo, Siena).
Fig. 13 'Woman at the window' (Frau am Fenster) by Caspar David Friedrich, 1822 (Nationalgalerie, Berlin).
Fig. 14 'Goethe in the window' (Goethe am Fenster) by Wilhelm Tischbein 1787 (Goethe Haus, Frankfurt).

between the columns) and exterior (merely visible in the upper part of the miniature). A medieval artist was unable to simultaneously render an indoor and outdoor setting in proportion and takes refuge in a paradox: the interior suggests a size several times larger than what the exterior depicts. Other examples of Lombardic art from the tenth century show an interest in how to visually render an interior, but there is a gap of a century and a half before the Italians embark on the road, which was to lead to the illusionistic interiors of the Master of Flémalle. It is only when the Italian masters of the Trecento have conquered the illusory technique to render three-dimensional spaces using perspective that coherence in the treatment of the relationship between indoors and outdoors is found. As an example, Nordenfalk points to the Birth of the Virgin, in the Dome of Siena, a reencounter with Dido's box-like interior from a thousand years earlier, but where the figures are 'no longer in front of the room, but inside it as its real inhabitants'.[38] [fig. 11] Besides this important difference, the door through which the maids have entered is integrated as part of a wall (although too narrow). Through an opening in the back wall, we are invited to look onto a square. This feature is borrowed from classical wall paintings, which often provided the illusion of an extension to an exterior - but, stresses Nordenfalk, the exterior is for the first time viewed through a simulated interior. A noteworthy contradiction is that while the bedroom has windows, we cannot see the outside sky.

It was a famous Parisian illuminator in early 15th-century Paris, Maitre Boucicaut, who provided the first outdoor view in a depiction of King Charles VI where the sky is noticeable from the royal bedroom, but without detail. This is where the achievement of the Flemish masters must be emphasised and why, in particular, the Master of Flémalle provides a poignant example. He invites us to watch Joseph as an ageing carpenter inside his workshop, from which a triple window offers a view onto the street, or a marketplace, of a Flemish town (see fig. 6, referred to above). As proposed by Nordenfalk, the mousetrap on the windowsill functions like a springboard for our own passage from the interior into the outdoor world, insisting on our inclusion, as spectators, in the painting. Still lacking skills in perspective drawing, the artist does not convince us that the workshop is located on the ground floor, nor is the relation between foreground and background accurately rendered. The work by other Flemish artists, such as Jan van Eyck, Rogier van der Weyden, and Jan Vermeer van Delft, bear witness to a similar struggle. They convincingly introduce a view through a window by which we, as spectators, are almost invited to communicate with the world outside.[39] Interior painting remained a strong genre throughout the eighteenth century. Whilst windows in architecture from this period tended to grow larger in size, paintings take a lesser interest in the view outside, where even back-walls are found to disappear into claire-obscure.

With the French Revolution and throughout the 19th century, a change in interest from interior to outdoor landscape painting is noticeable. The innovative work of Caspar David Friedrich fully concentrates on this theme and his seminal 'Woman at the Window' (1822) can be compared to Wilhelm Tischbein's depiction of Goethe by a window in Rome, forty years earlier. [fig. 12-13] In his endeavour to show how a spectator is involved in the communication between inside and outside, Nordenfalk uses these examples.[40] He compares the experience with that of being wrapped in darkness whilst immersed in a theatre play on a lit stage. In his reference to this as an 'invisible presence', where we, as spectators-in-action, now stand inside the space we share with the woman in the picture (who turns her back to us), Nordenfalk thankfully brings us back to the topic of my essay. He concludes: 'Whether we like it or not, we are as spectators taken into the picture, by being seated as passengers in the boat itself', this time referring to another painting by Friedrich, 'A Journey in a Gondola on the Elbe'.

Fig. 15

Fig. 16

Fig. 15 The focus of our excavation was a small island, which at the 1897 fair constituted a medieval replica called ‘Olde Stockholm’. It displayed an unspecified medieval atmosphere with buildings in half scale, simply constructed from wood and plaster and modelled on various medieval facades (Photo from www.stockholmskallan.se, Stockholm City Museum open archive).
Fig. 16 The same view of the island today shows that no visible traces of the 1897 art and industry fair remain.

In examining the designs for mediated spaces, such as the extension of the Museum of the National Antiquities in Stockholm to a neighbouring park area and excavation site, it may be asserted that spectators were similarly immersed in a shared activity, and that the mediated window, or glass-door, facilitated the experience of remote presence. The window here played the role proposed earlier by Mies van der Rohe: it gave shape to a museum space, opened it, and linked it to the landscape. We may discuss how materials, textiles and furnishings were combined to allow the human eye to experience an audiovisual architectural extension, as an interplay of reflection and transparency; and which design strategies were used to, as above, draw spectators into the picture.

Where the comparison to a conventional window clearly ends, however, is where we attempt to address the functionality of an exterior enclosing membrane, one that provides climatic protection or ventilation. Arguably, a window, or a door, can be opened and represents a passage between indoors and outdoors - a theme which has been treated very differently throughout architecture and art. A closer look at the framing and transparency aspects of the mediated window can illustrate a more detailed structure of gazing.

The mediated museum extension

The excavation which involved a spatial extension to the museum, created by means of a mediated window, concerned the remains of a renowned Art and Industry fair that Stockholm hosted in 1897. With 1.5 million visitors over six months, it was one of the largest public attractions in Sweden ever. The fairgrounds, located in a park area called Djurgården, constituted a pavilion city specifically designed for the event. In form and content, the numerous buildings expressed the high expectations and ambitions of a Swedish modern society, displaying industrial, societal, architectural and artistic innovations.[41] The fair is well documented but very few visible traces remain on the site today. Due to its importance, the large number of visitors and widespread souvenirs, the 1897 fair still reverberates in public memory. This part of Djurgården was frequently the setting for cultural events, even before 1897 and up to today. It is a very popular recreation area but, contrary to what its historical importance would imply, it is not recognised as a cultural heritage site. During two weeks in the summer of 2008, a part of the 1897 fair was therefore excavated as part of a collaborative process involving researchers at the Royal Institute of Technology in Stockholm, archaeologists, staff from the Swedish Museum of Antiquities and the general public. Our mission was to explore the way in which remote presence can inform cultural heritage processes, and the development of museum practices, today.

The focus of the excavation was a small island, to which there is usually no access, located by one of the main footpaths in the park. [fig. 14-15] At the 1897 fair a medieval replica was built here, inviting visitors to an unspecified atmosphere. Today, no visible traces from 1897 remain. However, we invited passers-by to participate in an archaeological excavation guided by professional archaeologists, and to contribute oral histories and objects relating to the fair. Intrigued by large photographic displays and an outdoor exhibit about the fair, people stopped to ask questions and many took a closer look. A temporary pedestrian bridge enabled people to join the excavation. Those who did were made aware of a mediated spatial extension to the Museum of National Antiquities: a mediated window, or glass-door, just by the excavation site. [fig. 16] This made face-to-face conversations possible in real time and enabled mediated presence to the museum interior from a remote location.

Inside the Museum of National Antiquities, a corresponding glass-door was designed, and integrated into our exhibition about the art and industry fair. [fig. 1] Approaching what can be referred to

Fig. 17

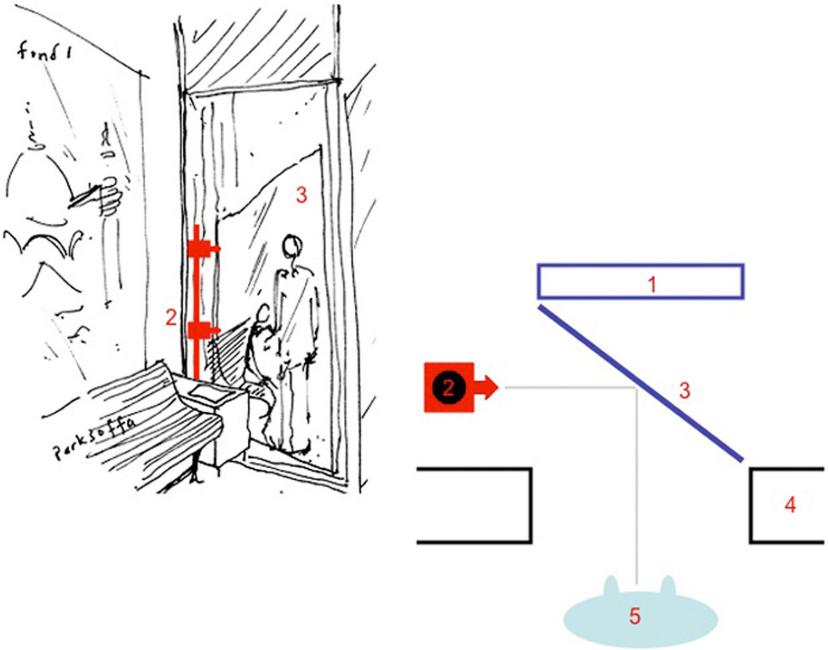

Fig. 18

Fig. 17 At the exterior location (the excavation site on the small island), a tent-like construction offered climatic protection for the combination of spatial and technical design that we have developed to enable mutual gaze in mediated spaces (see fig 19). Here, the glazing of the glass-door was slightly smaller than inside the museum, but of similar design.

Fig. 18 Illustration of the teleprompter-based design concept that enables mutual gaze, developed by Gullström & Handberg. Aiming to show that remote presence can be achieved at limited cost, our designs were based on modestly-priced, commercially available audiovisual communication equipment. Key: (1) Display of remote location; (2) Two video cameras located at an approximated child eye-level, and adult eye-level; (3) Sheet of glass at 45° (beamsplitter); (4) Exterior wall; (5) Museum visitor. To the left, my sketch of the planned extension of the park bench which would enable people to ‘share the same bench’.

as an ‘opening’ in the wall, a mediated ‘window’ or a ‘glass-door’, museum visitors would meet passers-by and archaeologists face-to-face, and were able to discuss and closely follow the activities at the excavation site. The verticality of the opening, its form and wooden framing, suggesting a glass-door with a horizontal bar, contributed to the architectural extension and experience of remote presence. In considering the design, the analogy of an open glass-door is perhaps more adequate than a window. The measures of the door (height 2m, width 0,9m) allowed visitors to meet face-to-face, to closely follow what was going on at ground level as well sensing the landscape, trees and surrounding sky. To avoid direct sunlight and optimise the light conditions for the cameras involved, black velvet textiles were used as a framing for the door opening. As seen from the photos, one would ‘stand in a doorway’ or ‘speak through’ the glass-door which appeared ‘left open’, since the design to enable mutual gaze included a sheet of glass placed at 45° before the opening. [fig. 17]

No ticket or prior booking was needed to visit the interior exhibition or the excavation, or to participate in the digging. Many of those who attended the excavation were passers-by, joggers or pedestrians, without a deliberate interest or intention to visit a museum. Many whose interests were caught paid a visit to the museum later. As a result of our project, both the museum and the cultural heritage site received many spontaneous visitors. In addition, a number of visitors participated in the activities remotely: almost 5000 people visited the excavation site in person over the two weeks, and about 2000 visitors participated remotely, from the spatially-extended museum interior.[42]

Designer observations

This was an attempt to treat the exterior landscape as an extension of the museum space by means of an opening in the façade: a mediated glass-door.[43] Features from the park, such as street signs, park furniture, and wall-sized backdrops of the landscape furnished the museum interior, suggesting that the interior and the exterior were treated as one continuous space. [fig. 1, 18] The border between interior and exterior was diffused, at least from the point of view of museum visitors. There was, however, a noteworthy difference concerning the ongoing activities in each location. For museum visitors, the noise and visible movements of people digging out of doors triggered curiosity and directed attention primarily in one direction: from the interior towards the exterior. There were sometimes large groups of people in both locations and we reflected that, in comparison with people at the excavation site, those inside the museum seemed to follow the museum convention of looking at (as opposed to looking through) rather than participate in, or interact with (cf. Lanham, op.cit.). They were classified as more passive observers, at least in comparison with people who were engaged in digging with the archaeologists or making sense of different visual media used to make passers-by aware of the activities and the 1897 fair.

What further strengthened the direction of gaze towards the exterior was the difference in lighting conditions. The museum space was darker and the attraction was towards the more noticeable exterior daylight filtering through the mediated window. From point of view of the excavation site - a busy outdoor workplace with lots of activities on a hot and bright summer day - one had to adjust one’s eyes to (what seemed) a dark museum interior.

After a few days, our team deliberately reinforced the effect of the directed gaze, by the decision to locate a box with previous findings ‘on the threshold’ of the mediated glass-door, precisely before one’s feet, as if standing inside the museum. [fig. 1, 19] This allowed a museum visitor to encounter the findings as if the objects were, almost, inside the museum space. In this sense, an architectural extension was achieved. Our design decision was

Fig. 19

Fig. 20

Fig. 19 Our exhibition design included outdoor features - for example, a grass-green carpet, a park bench and road signs - identical to the kind used in the park area. The resemblance to a 'real' door was created using a wooden framing that concealed vertical 46" displays (two inside the museum, one at the excavation site).
Fig. 20 Curiosity in the remote activities often inspired visitors to interact across the two sites, yet while they did, the direction of gaze from inside to outside appeared to dominate. Our design decision to place the findings' box on the 'threshold' between the museum and excavation site after a few days, contributed to the direction of the gaze: from interior to exterior. The findings' box can be compared to Flémalle's mousetrap strategy, described earlier.

based on the realisation that the findings box was a useful ‘conversation piece’ in the dialogue between visitors, staff and researchers on either side of the window. Walking around the excavation site on the small island, visitors would almost always ask: ‘What have you found so far?’ Those walking inside the museum were equally curious to see and hear what was going on outdoors. By pointing at the objects in the findings box, a conversation would be triggered, centred on the excavation and its context, and a dialogue developed to which people on either side of the ‘doorway’ would contribute. From the mediated dialogic interaction that followed, we observed how people interacted, and we sought confirmation that they were at ease, i.e. behaved more or less naturally, as if standing in a doorway.[44] Some would comment on the mediated glass-door and ask questions about its conception and technology, and some not all.[45] Although we did not attempt to evaluate this specifically, our observations are that such questions came after the visitor had sought - and received - sufficient feedback (from the remote party) to confirm that the mediated interaction could be trusted, which is in line with previous research on the experience of mediated presence.[46] To be able to achieve mutual gaze is an important design feature in this process. As designers, our observations during the user study served to tick off different signs that may confirm mediated presence, but our minds were always on the possible improvements we would make, next time, to make people feel even more at ease in a mediated space.

At all times, 6-10 archaeologists, researchers and museum staff were at hand in both locations and actively involved in the duration of the two-week project. Several of us, in effect, developed a role as ‘remote guides’ in the process of the project. From either side of the mediated glass-door we would engage people in conversation by talking about the excavation, the findings and the Art and Industry Fair, rather than about the mediated glass-door.[47]

Concluding remarks

My reason to explore Nordenfalk’s essay at such length was, of course, that it allowed me to address the similarities between design strategies at hand when contemporary artists, or architects, similarly invite us to share extended and mediated spaces. With regard to the design of the mediated museum extension, I suggest we can interpret this passage between indoors and outdoors in several related ways. My comments serve to show that the concepts of framing and transparency are applicable to presence design, but as is the case in architecture generally, it is the combination of many different design features that determines the overall effect of a design strategy. Nevertheless, it is useful to compare how the framing and transparency of the mediated museum example relates to those illustrated from the history of art and architecture.

Firstly, in terms of the mediated museum, I suggest that the inclusion of the spectator is carried out in ways not unlike what we encountered above in the seminal ‘Woman at the Window’ or indeed in the work of the Master of Flémalle. We are drawn to the mediated window by its strong light and intriguing activity (in stark contrast to the interior), both stemming from an exterior setting - not a marketplace, yet a crowded and populated excavation site. The fact that someone is often already standing or crouching by the glazed door, which means we see a person from behind, triggers our curiosity and invites us to join in, to share the space as a spectator-in-action. The role of the findings box can also be compared to that of the mousetrap in Flémalle’s painting: it acts like a ‘springboard for our passage from the interior into the outdoor world’. However, the transparency achieved by Bonnard is not possible here. A museum visitor can look through the glazing provided in the museum extension, but cannot reach out from the mediated window, or glass-door, as the lady does in ‘Dining Room in the Country’.

Secondly, I would like to remark on the integration of the mediated glass-door to the overall spatial design of the Museum of National Antiquities. While I will not directly imply that the medieval house-canopy applies to the mediated museum extension, its black textile framing was a foreign element in the spatial design of the museum as a whole.[48] This is an austere and sober building where openings are sharp and distinctly cut through heavy and load-bearing plastered brick walls without the involvement of textiles. Although the velvet textile served to improve the lighting conditions and established an intimate acoustic space in the proximity of the window, it almost created an enclosure, which infringed on the larger space, rather than a spatial extension. An alternative approach could perhaps have been to allow the window space to reach beyond the facade, similar to the way a bay-window functions. In considering the addition of an architectural element such as a mediated extension to an interior, which already has several marked openings, it might have been better to choose another wall than this façade.

My final comment concerns the way in which the design strives to establish a unity between indoors and outdoors. I suggest this worked better in one direction than in the other. From the museum interior, as from Bonnard's dining-room interior, we clearly experience that the exterior landscape is brought into the interior: the passage is free, and if we cannot feel how 'the sweet Mediterranean breeze fills the entire space' (which is how Nordenfalk qualifies the free passage from indoors to outdoors in Bonnard's interior), it is because we, instead, sense the birds and salt of the Baltic sea. Thus, the mediated museum window works as a passage from exterior to interior. As encountered from the exterior, however, it is less inviting and instead establishes boundaries. Undoubtedly, this can be linked partly to the ephemeral qualities of the temporary architectural context at hand, where a tent-like construction cannot be deemed a sufficient host for a window or a glass-door. Whether mediated or not, such architectural elements denote openings and must be integrated to more substantial constructions. Yet, there is no doubt potential for the mediated windows to also constitute an exterior architecture. As an architectural element, therefore, it remains to be seen how architects will find exterior usage for this capacity to establish synchronous, yet immaterial façade materials and spatial extensions. The aim here has not been a comprehensive account of how this may be achieved in architecture, but to address the potential contribution of architects to a currently diversified research field. With the claim that architecture and artistic practices are insufficiently represented here, I have sought to address a use of aesthetic concepts, imminent to architecture and related visual and digital practices.

Acknowledgements

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The project team took the photographs referred to in the text.

Notes

1. This paper draws upon research presented in my doctoral thesis where I apply the concepts of virtual and mediated space to architecture, proposing an extended architectural practice. I discuss architectural extensions that facilitate collaborative practices and explore the boundaries of architecture as a discipline by observing its assimilation of other media practices (Charlie Gullström, 'Presence Design: Mediated Spaces Extending Architecture', Ph.D. Thesis (Stockholm: Royal Institute of Technology, forthcoming 2010)).
2. The pilot study was carried out as part of the research project 'Remote presence to research heritage environments' 2006-08, as a basis for a continued research project 2009-11, also funded by the Swedish National Heritage Board: Cultural heritage processes and remote presence. As designers, I here refer to myself and Leif Handberg, Senior Lecturers at the Royal Institute of Technology (KTH), with assistance from Stefan Axelsson, Fredrik Hansen and Jacob Waller, diploma students in media technology.
3. Whether a frescoed wall, a cave mural, a digital projection or an Italian Renaissance perspective, virtual spaces are representations of space that we encounter on a surface. We may find ourselves immersed, by looking onto a surface in order to explore a three-dimensional reality, a vast panorama, a furious battle, a busy workplace or the fictional space of a book. Arguably, these are architectural extensions: mediated spaces. The history and theory of presence design can be drafted from concepts used in related visual practices, such as virtual space, mediated space, mediated gaze, spatial montage, shared mediated space, off-screen space, framing and transparency (Gullström, fortcoming 2010).
4. Mediated spaces by other architects and artists are worth mentioning. An early example is the temporary façade alteration of the Lincoln Center for the Performing Arts in New York, extended to a department store in Century City, Los Angeles, U.S. in 1980, designed by Galloway & Rabinowitz (www.ecafe.com/getty/HIS/); another is the media-space work environment that developed for a group of Xerox PARC researchers who were geographically divided between Palo Alto (California) and Portland (Oregon) in the early 1980s (see Steve Harrison (ed.), *Media Space: 20+ Years of Mediated Life* (London: Springer, 2009); Sara Bly, Steve Harrison, Susan Irwin, 'Media Spaces: Bringing People Together in a Video, Audio and Computing Environment', *Communications of the ACM*, 36 (1993), pp. 28-46. More recently, the façade alteration of HSBC on Canal Street, New York, projected time-lapsed images of passers-by in 2006, from designs by Yiu & Schuldenfrei (see Lucy Bullivant (ed.), '4dSocial: Interactive Design Environments', Special Issue of *Architectural Design*, Vol. 77: 4 (2007)), as well as the project Mirrorspace in Paris by the design group HeHe in 2003 (see Nicolas Roussel, Helen Evans, Heiki Hansen, 'Proximity as an Interface for Video Communication', *IEEE Computer Society*, Vol. 11, 3 (July/September 2004), pp. 12-16.). A project of related interest is the 'Hole in Earth' installation by artist Maki Ueda who created a permanent mediated extension between an urban public space in the Netherlands with a mosque in Indonesia throughout the year of 2004 (www.ueda.com), as well as the interior design by architects Waldvogel and Huang for the Swiss Consulate in Cambridge, Massachusetts, U.S. from 2000, which illustrates how large surfaces can be used for an integration of media technology and architectural elements (www.convergeo.com). Similarly, architect Holger Schnädelbach and colleagues at the 'Mixed Reality Lab' of the University of Nottingham, U.K. have developed a commercial concept called 'mixed reality architecture' which enables continuous and real-time video-mediated connection between office workspaces (www.mixedrealityarchitecture.com). This may be compared with my own architectural design for the iLounge media lab, a mediated space enabling remote participation and collaborative work, for a group of researchers in ubiquitous computing from 2002 (see Carl-Gustaf Jansson, 'Ubiquitous Working Environments', in *Designing User Friendly Augmented Work Environments*, edited by Saadi Lahlo (London: Springer, 2009)), and a workplace design for remote affinity in the archipelago 2004; for mediated unemployment services 2005; for a mediated therapist

2008 (Gullström, forthcoming 2010).

5. William Buxton, ‘Telepresence: integrating shared task and person spaces’, Proceedings of Graphics Interface ‘92 (1992), pp. 123-29. It can be argued that architecture by definition involves a ‘use of technology’, hence the definition would benefit from delimitation, such as ‘the use of communication technology’.
6. Presence research is primarily formulated from the perspectives of cognitive science and communication technology where studies in human cognition and perception have advanced the understanding of presence as ‘an individual experience’; a ‘perceptual illusion’ (see Matthew Lombard, Theresa Ditton, ‘At the Heart of It All: The Concept of Presence’, *Journal of Computer-Mediated Communication*, Vol. 3, 2 (1997), pp. 1-43; Richard M. Held, Nathaniel I. Durlach, ‘Telepresence’, *Presence: Teleoperators and Virtual Environments*, 1 (1992), pp. 109-12), or, as a ‘product of the mind’, regardless the technology at hand (Wijnand IJsellsteijn, Giuseppe Riva, ‘Being There: The Experience of Presence in Mediated Environments’ in Giuseppe Riva, G. and Fabrizio Davide and Wijnand IJsselsteijn (eds), *Being There: Concepts, Effects and Measurement of User Presence in Synthetic Environments* (Amsterdam: IOS Press, 2003)). It is a recently-established field and Lombard & Ditton’s 1997 article, entitled ‘At the Heart of it All: The Concept of Presence’, provides an important conceptual framework by summarising the contribution from researchers from cognitive science, neurology, virtual reality and computer graphics.
7. Lecture in Buenos Aires 1929, where Le Corbusier made this reference, stating: ‘architecture is lighted floors. I demonstrate it with a series of little sketches showing the history of architecture by the history of windows throughout the ages. As I said above, the object is to carry floors on walls that one perforates with windows in order to light the interior. And this thankless contradictory obligation (to carry floors on walls that one pierces) marks the effort of builders throughout history and gives architectures their character’. In Le Corbusier, *Précisions sur un état présent de l’architecture et de l’urbanisme* (Paris: de Crès, 1930), p. 55. Cf. English translation in Le Corbusier, *Precisions on the Present State of Architecture and City Planning*, trans. by Edith Schreiber (Cambridge and London: MIT Press, 1991), p. 52
8. Le Corbusier, *Vers une architecture* (Paris: de Crés, 1924).
9. Le Corbusier (1991), p. 52.
10. Kenneth Frampton, ‘Le Corbusier and l’Esprit Nouveau’, *Oppositions*, 15/16 (1979), 12-59 (p. 38). Cf. Kenneth Frampton, *Modern Architecture: a Critical History* (Michigan: Oxford University Press, 1980).
11. Kenneth Frampton, *Studies in Tectonic Culture* (Cambridge: MIT Press, 1995), p. 175.
12. Colin Rowe, *The Mathematics of the Ideal Villa and Other Essays* (Cambridge: MIT Press, 1976), p. 159ff. Cf. Stan Allen, *Practice: Architecture, Technique and Representation* (Padstow: Routledge, 2000), p. 114.
13. Carl Nordenfalk, ‘Outdoors-Indoors: A 2000-Year-Old Space Problem in Western Art’, *Proceedings of the American Philosophical Society*, Vol. 117, 4 (1973), pp. 233-58 (257).
14. Nordenfalk, p. 233.
15. See for example Anne Friedberg, *The Virtual Window: from Alberti to Microsoft* (Cambridge: MIT Press, 2006); Hisham Elkadi, Cultures of Glass Architecture (Aldershot: Ashgate, 2006); Isobel Armstrong, *Victorian Glassworlds: Glass Culture and the Imagination 1830-1880* (New York: Oxford University Press 2008).
16. Richard A. Lanham, *The Electronic Word: Democracy, Technology and the Arts* (London: University of Chicago Press, 1993), p. 5.
17. Frampton (1995), p. 173.
18. Cf. the quote from Le Corbusier, footnoted above.
19. Frampton (1995), p. 173.
20. Ibid.
21. Mies van der Rohe, in his ‘Address to the Union of German Plate Glass Manufacturers’, March 13, 1933. The quote appears in English translation in Wolf Tegethoff, *Mies van der Rohe: the Villas and Country Houses* (Michigan: Museum of Modern Art, 1985), p. 66.
22. Matilda McQuaid (ed), *Envisioning Architecture: Drawings from The Museum of Modern Art* (New York: The Museum of Modern Art, 2002), p. 70.

23. See e.g. Elkadi.
24. Julian Henderson, Matthew Ponting, ‘Scientific Studies of the Glass from Frattesina’, *Bead Study Trust Newsletter*, 32:3 (1999). Cf. Julian Henderson, *The Science and Archaeology of Materials: an Investigation of Inorganic Materials* (Glasgow: Routledge, 2000).
25. Michael Wigginton, *Glass in Architecture* (London: Phaidon, 2002).
26. William Arnold Thorpe, *English Glass* (London: A & C Black, 1949).
27. See e.g. Armstrong.
28. Walter Benjamin, *Reflections: Essays, Aphorisms, Autobiographical Writings*, edited by Peter Demetz, trans. by Edmund Jephcott (New York: Schocken, 1978). Cf. Susan Buck-Morss, *The Dialectics of Seeing: Walter Benjamin and the Arcades Project* (Cambridge, Mass.: MIT Press, 1991).
29. See for example Alan Colquhoun, *Modern Architecture* (Oxford University Press, 2002); Nikolaus Pevsner, *Pioneers of Modern Design: From William Morris to Walter Gropius* (Harmondsworth: Penguin 1960); Frampton op. cit (1980).
30. Rayner Banham, ‘The Glass Paradise’, *The Architectural Review*, 125 (February 1959), pp. 87-89.
31. Quoted by Banham.
32. See e.g. Frampton (1980).
33. Nordenfalk, p. 233.
34. See for example Heinrich Drerup, ‘Bildraum und Realraum in der römischen Architecktur’, *Römische Mitteilungen des Deutschen Archäologischen Instituts*, 61 (1959), pp. 147-74; John Clarke, *The Houses of Roman Italy, 100 B.C. - A.D. 250: Ritual, Space and Decoration* (Berkeley: University of California Press, 1993).
35. Nordenfalk, p. 235.
36. Nordenfalk, p. 236.
37. Nordenfalk, p. 239.
38. Nordenfalk, p. 241.
39. Nordenfalk points at how Vermeer’s famous painting ‘Young Woman with a Water Jug’ provides an ‘intense feeling of a silent dialogue between interior and exterior’ as the woman is about to open the window (Nordenfalk, p. 247). The woman and the window are here placed very close to one another, in a way that would have been impossible in classical or medieval art, where an indoor setting was implied, merely by the placement of figures on a floor, seen in perspective.
40. He notes that the size of the window is much larger than ever before and the contrast between exterior daylight and dark indoor lighting is dramatised: ‘as if we were peeping through the keyhole of a dark chamber into the full light of another’ (Nordenfalk, p. 248). Whereas the old masters rendered an interior as a world *per se*, a space separated from us through an invisible membrane we could not pass, we are suddenly invited as spectators into the room: ‘Here for the first time we have the impression of having slipped into the room, sharing its view outdoors with the inhabitant’ (Ibid).
41. See e.g. (in Swedish) Anders Ekström, *Den utställda världen: Stockholmsutställningen 1897 och 1800-talets världsutställningar* (Stockholm: Nordiska Museet 1994); Anders Ekström, Solveig Jülich, Pelle Snickars, *1897 - Mediehistoirer kring Stockholmsutställningen* (Stockholm: Statens Ljud- och bildarkiv, 2005); Ulf Sörenson, *När tiden var ung. Arkitekturen och Stockholmsutställningarna 1851, 1866, 1897, 1909* (Stockholm: Monografier utgivna av Stockholms stad 140, 1999); Hans Hildebrand, Fredrik Lilljekvist, Gustaf Upmark, F. U. Wrangel, *Stockholm under Medeltiden och Vasatiden. Kort framställning jämte förare genom gamla Stockholm* (Stockholm, 1897); E.G. Folcker, “Gamla Stockholm”, in *Allmänna konst- och industriutställningen i Stockholm 1897. Officiell berättelse. Utgiven på uppdrag af förvaltningsutskottet*, edited by Ludvig Looström (Stockholm, 1899).
42. The excavation site was within walking distance (10 minutes) from the museum and the project was partly carried out in the interest of attracting more and new categories of visitors to the museum. The Museum of National Antiquities later credited the project for an increase in the total number of museum visitors recorded in August 2008 (17,667 visitors in comparison with 10,957, in August 2007). This count does not include the visitors to the island, but it can be discussed under which conditions remote participation and mediated interaction qualifies as a ‘museum visit’.

43. The design was the outcome of a prototyping process in which we attempted to make as large a wall opening as possible, but found that a door-sized opening would ensure the best conditions for mediated interaction, in this context. The reasons were partly budget-related (we had limited budget and time), climate-related (it was difficult to forecast the negative effects of August sunshine and we had to consider the problems that rain might cause), and theft-related (we had no means to supervise the excavation site at night and had to dismantle the installation every evening). Thinking it would be more adequate for the outdoor solution, we first planned to use back-projection on large matted displays. Although our prototyping proved fruitful, and has been used in our subsequent designs, we abandoned back-projection and opted for displays, shielding the seam of the two with a wooden frame, thus referring to the design of a door, as described above.
44. Coleridge's 'willing suspension of disbelief' is commonly used in media-technology discourse, in reference to how viewers, in the prospect of entertainment may temporarily agree to suspend their judgment. The English poet and philosopher Samuel Taylor Coleridge used the phrasing in the context of writing and reading poetry in his *Biographia Literaria*, published in 1817.
45. We would answer such questions briefly but tried to avoid a mediated interaction being dominated by a conversation on technology. If needed, we would take a person to the side and give a full account of the combination of spatial and technical design that enables mutual gaze in mediated interaction. Based on previous design experiences our aim was to assert to which extent our embedded design and certain features contributed to 'being at ease' in this specific context. The experience of mediated presence is individual and related to prior knowledge and experience of the user. Therefore, it was deemed important to confirm that once a mediated dialogic interaction took place, those involved behaved quite naturally towards each other. From previous prototyping we have, for example, learned that if technical equipment is visible or requires monitoring, some users feel insecure. This is one reason why the cameras and other equipment is embedded and that nothing needs to be managed by the user in our designs of continuous mediated spaces.
46. Possibly due to the widespread use of displays (e.g. showing moving images) in museum contexts, visitors often adopt a role as passive observers. The effect is that a person does not always consider that what they see (e.g. a mediated glass-door) might be a projection in real time. We have often noticed that it takes a moment before this realisation occurs. This is part of a confirmation process in which feedback from the remote party is crucial and related to trust, as a prerequisite for the experience of (witnessed) mediated presence, see e.g. Caroline Nevejan, 'Presence and the Design of Trust', Ph.D. Thesis (Amsterdam: University of Amsterdam, 2007); Wijnand IJsselsteijn, 'Presence in Depth', Ph.D. Thesis (Eindhoven: Eindhoven University of Technology, 2004). Our decision to design a 'door' relates to our interest in letting users 'trust' the environment: a door is perceived quite differently from a 'TV display'. In this case, the door effectively concealed the displays, placed vertically to avoid an association with the familiar 16:9 format of film and television media. There are, of course, many other ways to integrate spatial and technical design.
47. Depending on their individual expertise, each researcher would contribute e.g. archaeological, architectural, historical etc perspectives in such mediated interaction. Those of us who had worked on the combination of spatial and technical design agreed on a role as participating observers prior to the event. We took turns and stood nearby each window/door engaging in conversation on the topic of the excavation and its context rather than on the technical conception. We would later discuss our experience and observations amongst ourselves. The reflections and observations presented here are based on discussions with the other KTH researchers and on interviews with the participating archaeologists and museum staff.
48. There is, possibly, a comparison to be made with the miniature by the Master of the Registrum Gregorii (see fig. 10), whose curious scribe is present, yet in a separate space from which he can see and hear - a

strategy of transparency created by means of textiles, which have been draped around the classical interior as a temporary measure. One of the textiles appears velvet-like in contrast, and has been drawn thus revealing a small spatial extension.

Biography

Charlie Gullström is a Senior Lecturer in architecture, media, interaction and communication at the Department of Architecture, Royal Institute of Technology (KTH), Stockholm. Her research and practice seeks to extend our conception of the discipline of architecture by examining the contribution of media, interaction and communication - specifically, the fusion of architecture and media technology that enables mutual gaze in dialogic interaction (mediated spaces, presence design). In 2010, she will present a doctoral thesis entitled Presence Design: Mediated Spaces Extending Architecture. She holds a Tekn. Lic. Degree in Architecture (1994) and a M.Sc. Degree (1990) in Architecture from KTH. Charlie Gullström is also an experienced architect; from 1990-2005 she led a widely-renowned practice in Stockholm, specialising in the design of spaces in which learning, collaboration and communication are central, explicit concerns for leading Swedish corporations and educational institutions.

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