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Allotropic Fields - On Architectural Kinetics & Biodynamic Assemblies

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ALLOTROPIC FIELDS _ ON ARCHITECTURAL KINETICS & BIODYNAMIC ASSEMBLIES

by

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Abstract

Through the recent prevalence of interdisciplinary design, kinetic architecture has aligned its modalities with those of biological paradigms. Homologous to transformative architecture, biological organisms exemplify a propensity for adaptation by virtue of kinetic means. Along these lines, the institution of kinetic architecture, hitherto delineated by hard mechanical means, is transitioning to soft, polymeric material systems analogous to homeostatic mechanisms. While this signals the beginning of a paradigmatic shift, architectural kinetics – nascent by its own right - finds itself only in the incipient stages of establishing a framework rooted in the operative analogies of dynamic biological behavior. With the intent of furthering this burgeoning discourse, this thesis explores the interface between mechanisms of biological adaptation and architectural kinetics in order to cultivate new transposition strategies and, in turn, develop an architectural prototype embodying novel manifestations of kinetic complexity and dynamism.

acknowledgements

I would like to thank John Cirka, my thesis supervisor. This thesis is effectively the culmination of a four year period in which John has played a critical role in my development as a designer and architectural researcher. I credit John as the one who inspired and later encouraged me to integrate my background in biophysiology into the framework of my graduate research in architecture.

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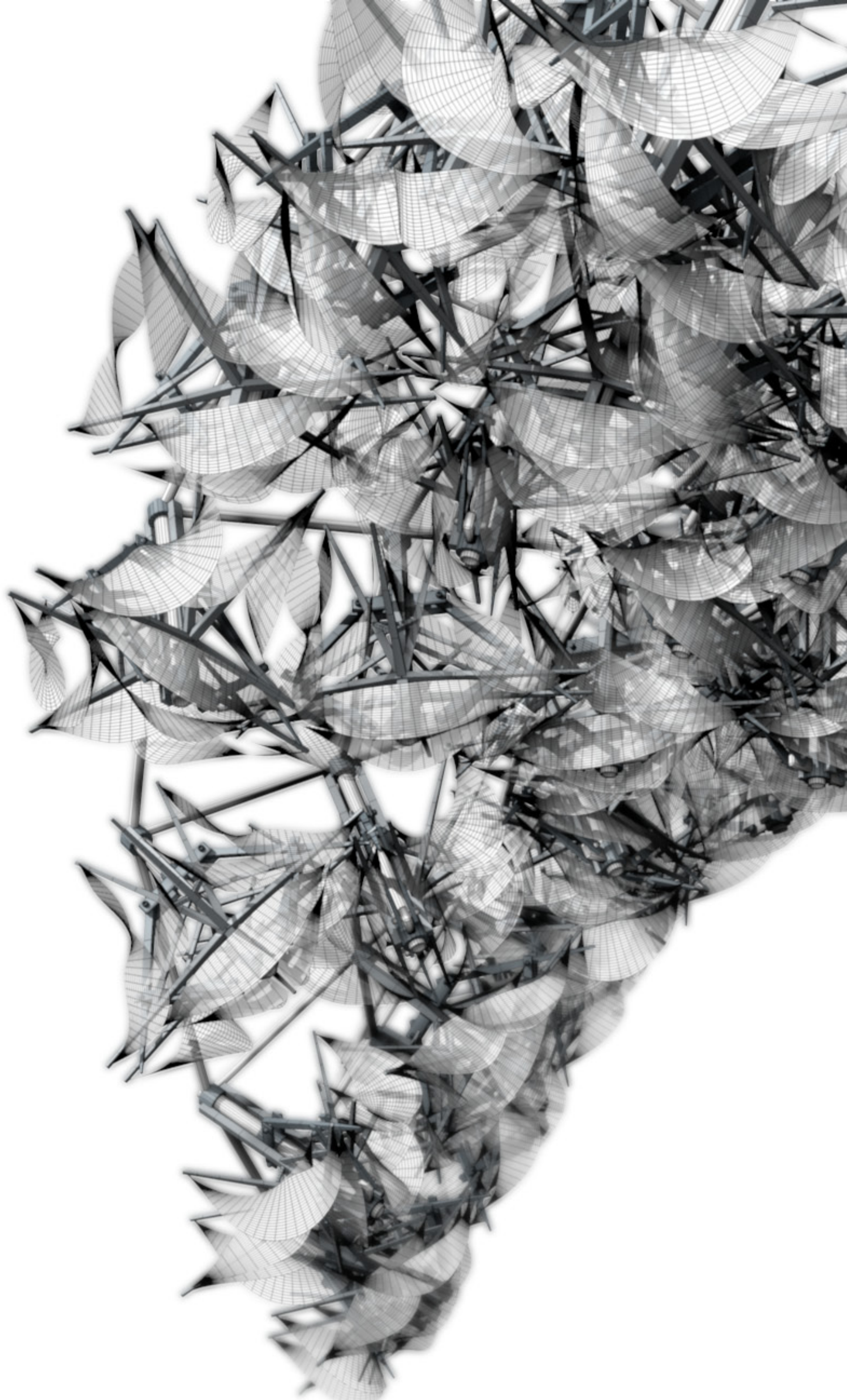
list of illustrations

list of appendices



allotropic fields

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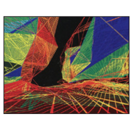
_ on architectural kinetics & biodynamic assemblies

Introduction

In a wireless era characterized by electro-nomadic spatial practices - as described by William J. Mitchell in his seminal work: *Me++: The Cyborg Self and the Networked City* – the relationships between buildings and their occupants is changing in a profound way. Mitchell describes the advent of mobile technology as having enabled self-sufficiency, which has prompted individuals to rely less upon the fixity of people and places and in turn rely more upon a new category of human assemblage predicated on 'a spatially dispersed yet coordinated, fluid collections of wirelessly interconnected individuals' (Mitchell, 2003). This culture of electro-nomadism has engendered an important destabilization of person-to-place relationships and has precipitated a critical redefinition of the *architectural program*, from a spatial organization strategy to a temporal one. Traditionally, the architectural program has rigidly delineated the spatial division of a building, such that a space is specialized to accommodate a particular activity. Mitchell argues that such static programmatic strategies are incompatible with the mobility of contemporary nomadic culture: one in which electronic fields of presence engage with many different activities at a single location or the same activity at many different locations. Architecture must thus respond by creating flexible, diverse, humane habitats for electronically supported nomadic occupation (Mitchell, 2003).



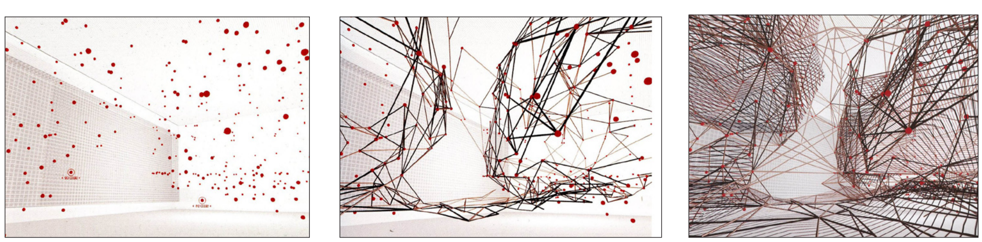


figure 1: *Jväskylä Music and Arts Center* by Ocean North

Robert Kronnenberg, in *Transportable Environments*, elaborates on the role of architecture in response to shifting paradigms of technology-driven social interaction. Kronnenberg argues that through the emanation of electro-nomadism, the architectural space has lost specificity as defined by a particular architectural description of programmatic needs. In turn, typological spaces have homogenized to become universal in a sense. 'The café was a library, study, meeting place and an address, a place which blurred the distinction between being at home and being out-and-about' (Kronnenberg, 1998). Within a framework where typologies begin to blend and become interchangeable, he continues, it is increasingly necessary to develop an architecture of kinetic forms capable of adapting to a range of *pressure* changes inherent in a society immersed in high magnitudes of dynamism.

Historically, architectural kinetics have been characterized by functional adaptability. The lineage of kinetic architecture has engendered wide-ranging mechanisms to respond to pragmatic pressures including, but not limited to shelter, space efficiency, security and economics. Contemporaneously, the framework of kinetic architecture transitioned from one predicated on adaptability to one of *adaptivity*. The annexation of kinetic componentry and automated systems of sensory-actuating feedback enabled a shift from architecture that which *can be adjusted* towards architecture possessing *an inherent nature to adjust*. Kinetic architecture is thus no longer measured solely against criteria of mechanisms of effect. The indices of affective control, formerly regulated by the motives of user occupancy, are now able to operate by means of computational mediation, through which architecture is developing a capacity to sense actual contextual conditions to, in turn, react by virtue of physical, real-time changes.

Through a proliferating framework of computational sentience, kinetic architecture potentiates new strategies to engage with the technologically influenced and changing patterns of human interaction with the built environment, as posited by Mitchell and Kronnenberg. In *Interactive Architecture*, Michael Fox further describes kinetic function through technological design strategies for building types that are inherently flexible with respect to various contexts and a diversity of purposes. While he expounds a thorough analysis of kinetic strategies and associated means of operability, his rationale is particularly insightful on account of his discussion of kinetic architecture in both mechanistic and biological terms. He argues that kinetic architecture, by the agency of recent technological developments, is undergoing a paradigmatic shift, from the mechanical to the biological, from a standpoint of adaptation.

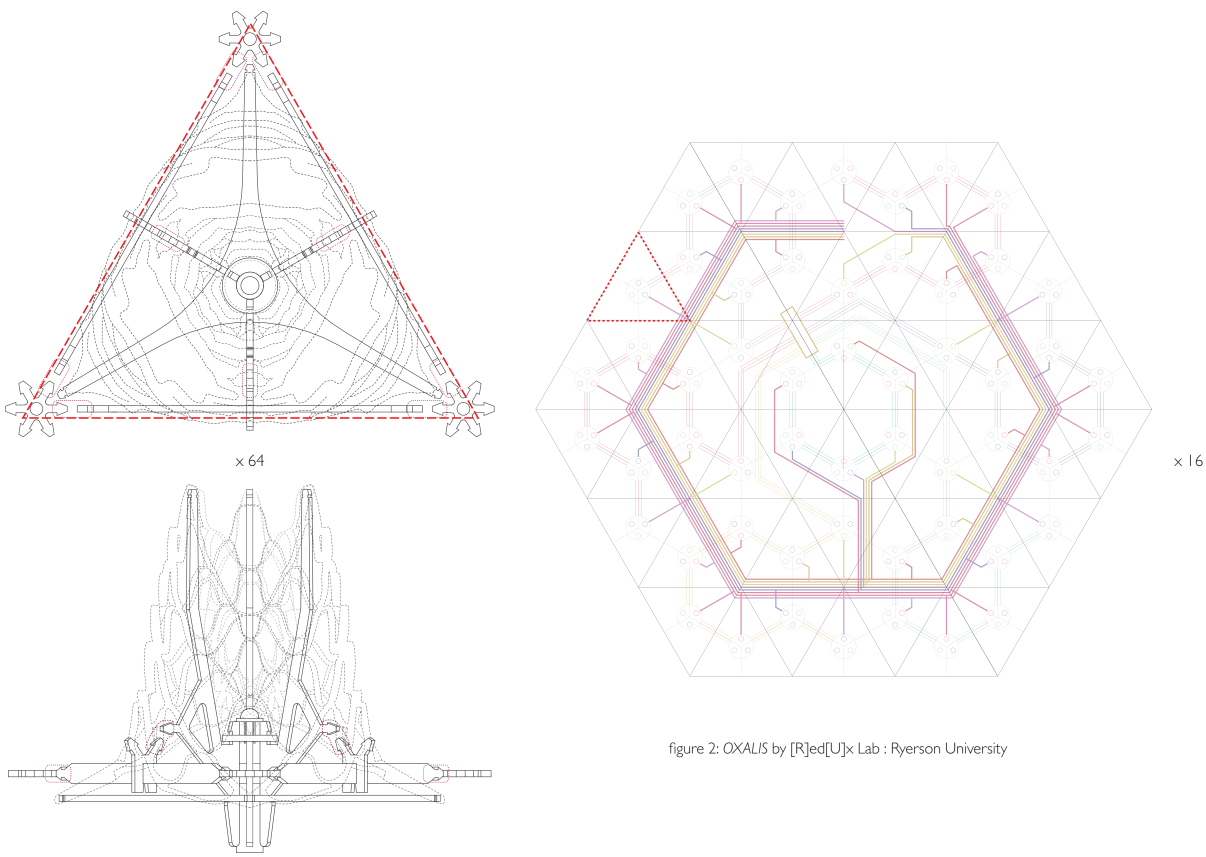
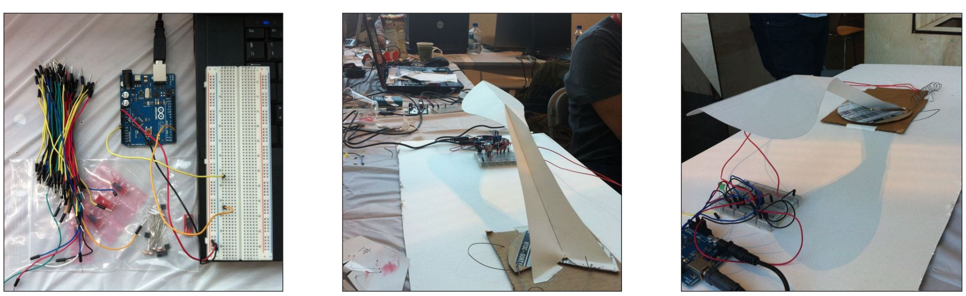


figure 2: *OXALIS* by [R]ed[U]x Lab : Ryerson University

Fox characterizes the prevalence of this biological realignment as a result of the development of compliant material systems and their role in designing and building environments that address changing needs. The appropriation of soft, form-changing material systems, brought upon by the confluence of architectural design with biomaterial sciences, has produced new means of affecting physical transformation and kinesis in architecture. Rather than adapting through disparate mechanical elements and technologies of connections, he argues, polymeric material systems actuate movement and change according to intrinsic material behavior. By means of material self-organization, polymeric systems thus enable stable adaptation towards structural integrity while exhibiting dynamic response to extrinsic stimuli. This allegory of material behavior resonates with the mechanisms of homeostasis - a fundamental driver of biological adaptation, regulating metabolic constitution through networks of material interrelations (Fox & Kemp, 2009).



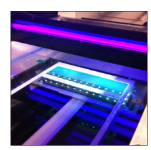


figure 3: *Smart Geometry 2012 _ Beyond Mechanics Micro-synergistics*

Gary Brown, in his introductory text of *Transportable Environments*, provides a rationale for the emergence of a physically adaptive architecture arising out of human needs and supported by an improved understanding of biological systems: '(It) emerges from nature, an environment that possesses evolutionary patterns that have a base code and an inherent program where information is strategically interrelated to produce strategies of behavior, optimizing each particular pattern to the contextual situation' (Brown, 1998). This prevalence of biological systems over mechanical systems, he continues, has altered the conceptual model that we apply in order to comprehend our environment and, consequently design our environment. In turn, this organic theory is emerging from the performative aspects of the operational scale and the inherent behavior of materials as well as the role that innovative materials may play in designing and building environments that address changing needs.

While figurative homologies inherent in polymeric material systems and homeostatic processes signal an emerging alignment between architectural kinetics and mechanisms of biological adaptation, the question becomes how to establish a collateral platform from which indices of kinesis can be transposed from the organic to the architectural. Furthermore, in dealing with the operants of biodynamics and those of architectural kinetics, how does one negotiate discrepancies in complexity, materialities and hierarchies? With the aim of engendering novel transposition strategies, this thesis explores biomechanical precepts implicit in animal locomotion and complex biokinetics for the purpose of developing an architectural prototype embodying new expressions of kinetic variability and dynamism.

In order to delineate the genealogy of kinetic architecture it is necessary to first clarify its definition as well as its relationship with other time-based architectures. As previously mentioned, kinetic architecture denotes a term describing the capacity of architectural components to engage with motion. A clear distinction is required to differentiate kinetic architecture from other architectural praxes embodying temporality and movement, such as:

- Transformation through the event of occupation
- Weathering of materials and effects of decay
- Representation of motion through dynamic appearance of form and surfaces
- Spatial distortion resulting from fluctuations of light

Kinetic architecture, within the framework of this thesis, will thus refer to the potential of movement inherent in transformative architectural structures – including:

- Kinetic systems existing within a larger architectural whole in a fixed location, controlling the larger architectural system, in response to changing factors *or* acting independently with respect to control of the larger context
- Kinetic systems existing in a temporary location and easily transportable with an inherent capability to be constructed and deconstructed in reverse.

Within the parameters of this definition, I will subdivide kinetic architecture into adaptive and adaptable architecture. Adaptive architecture will denote a capacity of building componentry to sense contextual pressures and in turn, through reflexive systems of computational logic, react by real-time spatial transformations. Conversely, adaptable architecture simply refers to kinetic architecture that is not adaptive or, to kinetic systems operating outside the realm of the 'sensor-processor-actuator' model epitomized by adaptive architecture. Generally, adaptable architecture encompasses indices of kineticism devoid of sensory *and* processing capacities. In this classification, kinesis can be initialized through user occupancy or computation systems, and actuated by means of any energy source. The two sub-terms employed to further differentiate adaptable includes: programmable and reactive. Programmable architecture refers to kinetic architecture actuated through computational mediation albeit deficient in extrinsic, sensory capabilities. Kinetic actuation in programmable architecture occurs insularly through the framework of coding language. Reactive architecture refers to kinetic architecture capable of a direct response to a singular stimulus. This definition precipitates an important schism vis-à-vis adaptive systems, which under the influence of external forces, either environmental or by human intervention, do not produce a correspondingly direct reaction. Rather, these inputs are processed according to the logic of the control system to produce a *reflexive* kinetic response.

Within the frame of adaptive architecture, a partial appropriation of Fox and Kemp's *Interactive Architecture* (2009) typology system will be used to categorize its subdivisions.

- Adaptive In-Direct Control

The basic system of operation is the same as in programmable systems, however the control device may make decisions based on input from a sensor(s) and make an optimized decision to send to the energy source for the actuation of movement for a singular object.

- Ubiquitous Adaptive In-Direct Control

Movement in this level is the result of many autonomous sensor/motor (actuator) pairs acting together as a networked whole. The control system necessitates a feedback control algorithm that is predictive and auto-adaptive.

- Heuristic Adaptive In-Direct Control

Movement in this level builds upon either singularly adaptive or ubiquitously adaptive self-adjusting movement. Such systems integrate a heuristic or learning capacity into the control mechanism. The systems learn through successful experiential adaptation to optimize a system in an environment in response to change.

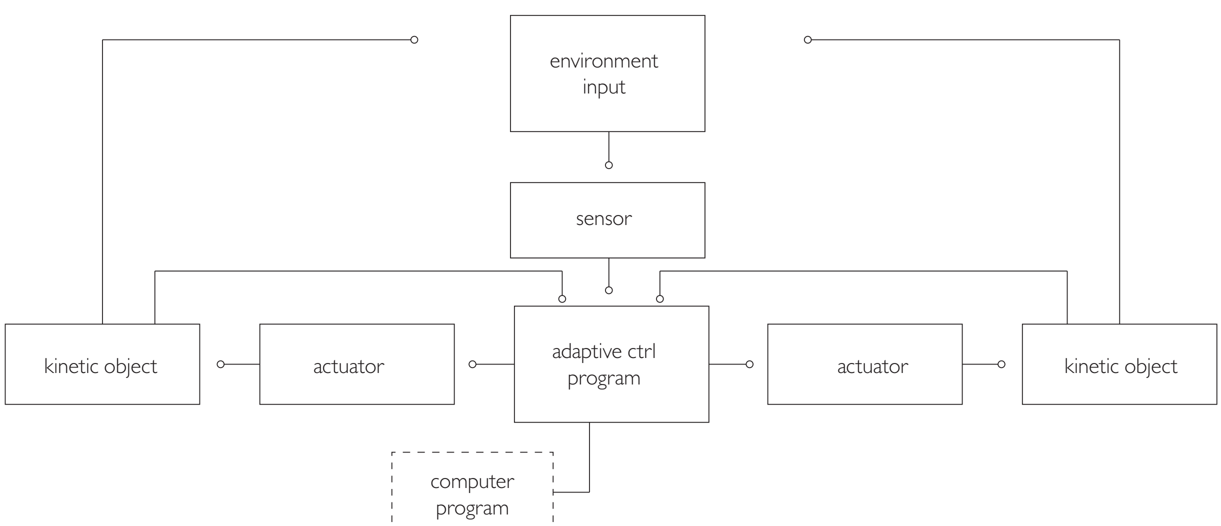


figure 4: *Interactive Architecture Taxonomy Scheme by Michael Fox*

Lineage

This section examines the lineage of adaptive design and its emergence through the ontogeny of kinetic architecture in the twentieth century. This interval originates with the emanation of Italian Futurism – a precursory movement to Modern Architecture - fuelled by the artistic and social ideologies glorifying modern technology and the power of the machine and industrialization. This provides an interesting point of departure as it traces the incipient convergence of notions of kineticism with precepts of architectural theory.

The creed of the Futurist philosophy first materialized in 1909 through Marinetti's *The Founding and Manifesto of Futurism*. In this influential work, Marinetti denounced the cultural heritage of Italy and all previous classical artistic traditions and in turn championed speed, machinery, industry and the technological triumph of humanity over nature.

We will sing of great crowds excited by work, by pleasure, and by riot; we will sing of the multi-colored, polyphonic tides of revolution in the modern capitals; we will sing of the vibrant nightly fervor of arsenals and shipyards blazing with violent electric moons; greedy railway stations that devour smoke-plumed serpents; factories hung on clouds by the crooked lines of their smoke; bridges that stride the rivers like giant gymnasts, flashing in the sun with a glitter of knives; adventurous steamers that sniff the horizon; deep chested locomotives whose wheels paw the tracks like the hooves of enormous steel horses bridled by tubing; and the sleek flight of planes whose propellers chatter in the wind like banners and seem to cheer like an enthusiastic crowd (Marinetti, 1973).

Beyond the articulation of mechanized urban settings, the Futurist conceit also included architectonic expression interlaced with machinal dynamism. In 1914, Prampolini's *The Futurist Atmosphere-Structure*, envisaged architecture's new kinetic future to

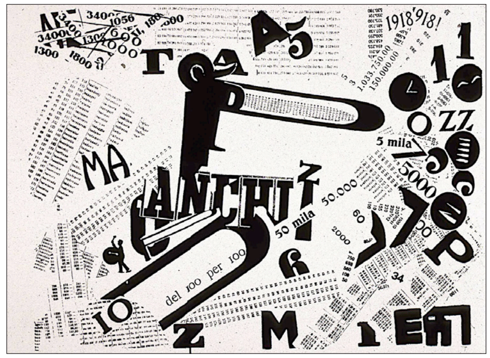


figure 5: *The Founding and Manifesto of Futurism by Marinetti*

be formed by the external energies of a society in technologized transition and shaped by 'motion, light, and air' (Prampolini, 1973). This sentiment was further substantiated by the credence of Antonio Sant'Elia who argued for architecture's reinvention in light of the urban transformation taking place in the culture of speed. The Futurist city would be 'agile, mobile, dynamic in every part and the modern building, described through assemblages of swarming elevators, conveyor belts, and suspended catwalks, must be similar to a gigantic machine' (Banham, 1980).

Notwithstanding thetic justifications for a machine architecture, the Futurist axiom was primarily ideological, concerned with rhetoric rather than formal or technical methods. The Futurist involvement in the cult of technology was thus defined through the machine as an aesthetic model offering lessons of order, discipline and force rather than machine as an archetype in materialized kinesis.

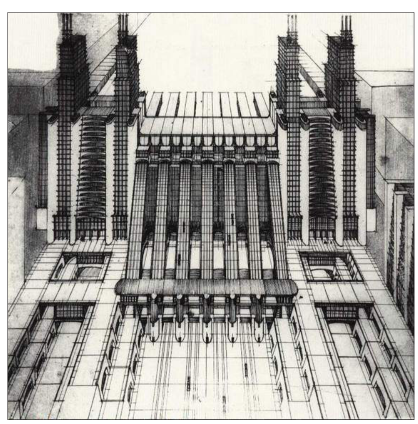


figure 6: *Viziunea Futurista by Sant'Elia*

Through the framework of constructivism, architectural theorization of the machine and technology drew closer to the actualization of movement. Constructivist architecture, which gained cultural authority and official sanction in the years following the 1917 Russian Revolution, combined advanced technology and engineering with socialist ideologies. Contrary to Futurist notions of kinesis, which laid latent in paper architectures and figmental descriptions, the aspirations of the Russian avant-garde envisioned the machine playing a more systematic role in architectural conceptualization. Constructivism's reach into architectural kineticism was primarily defined by that which would interact with its environment – architecture that would dynamically engage with the masses, bearing the icons and letterforms of media and typographic symbols of the oncoming age of advertising and design. Influenced by the new media of motion pictures and radio coupled with a yearning to integrate aesthetic and technological-scientific forces, the Constructivists proposed an architecture that sought to make manifest the new machine age in appearance, form and materials (Salter, 2010).

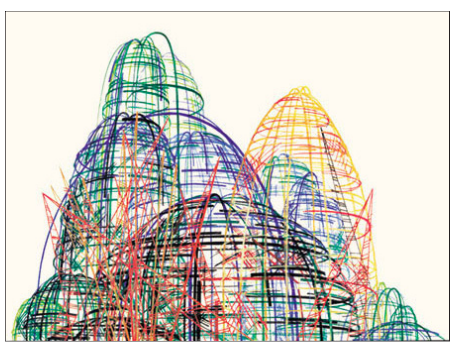


figure 7: *Architectural Fantasies by Chernikov*

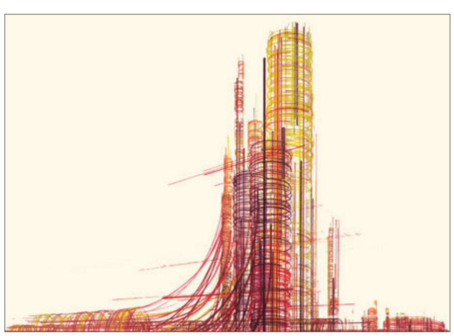


figure 8: *Architectural Fantasies by Chernikov*

In 1924, Moisei Ginzburg, the foremost proponent of Constructivist architecture, published *Style and Epoch*, an influential text calling for a fusion of engineering, architecture and socialist ideals. With imagery of grain elevators and American factories combined with Russian experiments in architectonic expression, *Style and Epoch* sought to formulate a new socio-technical reality through the appropriation of machine principles, which provided an ideal organizational model to determine the functional course of a building.

Neither the machine nor the engineering structure provides us with an expressive spatial solution, one that constitutes a true manifestation of architecture. Our assimilation of this method will be made somewhat easier by an analysis of another kind of structure, which also emanates directly from the machine but which already bears greater affinity to what is termed architecture – namely, industrial structures. The factory is the most natural consequence of the development of the machine. It unites within itself a whole assembly of machines, which are sometimes homogenous, sometimes heterogeneous, but always bound together by one and the same common purpose. Such an assembly of machines is imbued by a movement that is infinitely more intense than that of each individual machine; at the same time, the heterogeneous machines that are united by one common purpose are an example of an even more striking and orderly compositional organization (Ginzburg, 1982).

Ginzburg's analogies on the operative parallels of machine technology and architectural design established an important theoretical platform from which other architects furthered Constructivist ideologies. *The Construction of Architectural and Machine Forms*, a 1931 work by Iakov Chernikov, embraced a congruent understanding of the machine: hypothesizing the machine as an ideal model for construction. Composed of a series of pure, almost monumental forms, uniting disparate parts or objects into a functioning whole, the machine not only enabled the insertion of one element into another with all the possible individual variations and combinations, but also generated what

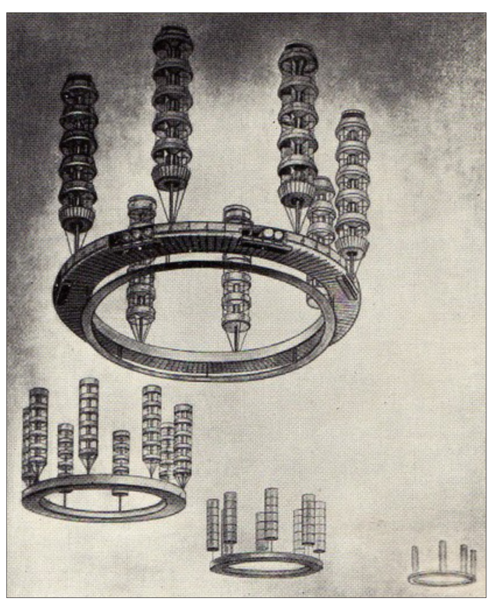


figure 9: Designs for a Utopian Future by Krukitov

Chernikov labeled *constructive dynamics*. Chernikov's works featured an industrial vocabulary of kinetic elements that brought to life the sense of motion implicit in his designs. Although this mechanical nature demanded that movement of some sort take place, the architect conceded that buildings were static; their potential for real kinetic movement disappeared in time (Salter, 2010).

Much like the imaginary schemes of Chernikov, the work of other Constructivist architects, which drew up grandiose plans for cityscapes inhabited by entirely kinetic buildings, were never actualized in physical form. As with their Futurist contemporaries, constructivist designers worked in a dynamic, heady atmosphere that, because few resources were available for building, often turned to utopian architectural fantasy. Art critic Robert Hughes (2006) noted that 'there was hardly enough surplus wattage in all of Moscow to run an egg timer'. Despite the economic and political instability of prewar European societies that made such techno-social experiments in construction unachievable, the Constructivist (and Futurist) movements succeeded in establishing the theoretical underpinnings of an architecture released from the traditional constraints of gravity and stasis.

Beyond the seminal annexation of kinetic conceit to the framework of architectural theory, the rapid pace of technological innovation of the twentieth century engendered the realization of important kinetic projects, namely in residential architecture. Advancements in machinery, materials and electricity brought push-button automation into the home and with it the promise of gadget-enabled ease and convenience (Randl, 2008). Novel mechanical technologies coupled with modernist tenets of functionality and spatial efficiency prompted innovative designs for kinetic systems in the context of residential interiors. Developments in adaptable componentry such as foldable furniture and internally rotating partitions aimed at addressing the perceived drawbacks of conventional dwellings with rooms dedicated to specific purposes. In 1918, Pascale Cimini patented a four-section turntable that incorporated a dresser, bed closet, and a kitchenette equipped with a sink and stove. Anchored on a grooved ball-bearing track recessed into the floor structure, a central standpipe with revolving connector sections riding on ball-bearing mounts linked the faucets and drains on the turntable to stationary pipes in the building. This intricate composition of latches, springs, gears, casters, cables, weights, and hinges permitted the furnishings to emerge into the room for use and to then retract by rotation (Randl, 2008).

The first half of the twentieth century also saw large-scale articulations of kinetic architecture in the form of rotating houses. While internal kinetic systems focused inwardly to improve spatial qualities and efficiencies, externally rotating houses focused on environmental mediation. These designs not only offered angular positional control in relation to the sun and wind to maximize user comfort, but also expanded the range of views available to the occupant. Despite the mechanical viability of rotating houses and ample scientific evidence for their advantages, few of these schemes were realized. One of the few rotating structures to find a place in published histories of architecture is Villa Girasole - an externally rotating house developed by Angelo Invernizzi in 1935. The structure is composed of two

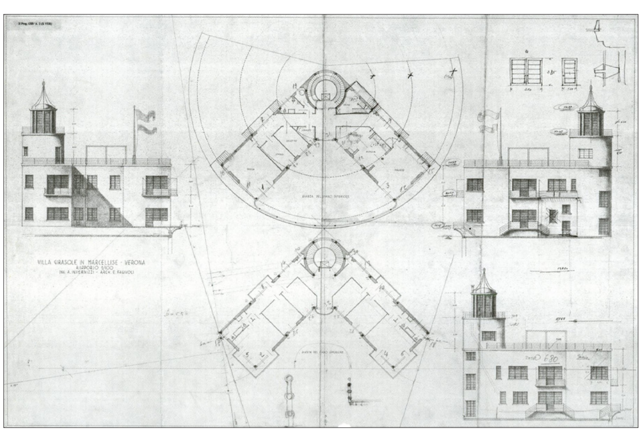


figure 10*: Villa Girasole by Invernizzi*

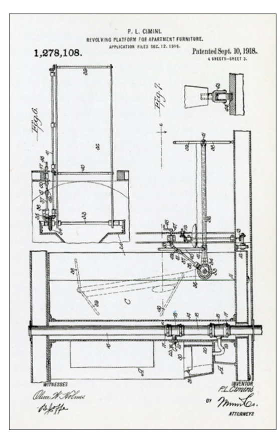


figure 10b*: Four-Section Turntable by Cimini*

L shaped storeys, rotating over three circular tracks to follow the sun. A central 42 meters conning turret served to hinge a series of rotating platforms, from which a diesel engine and two motors pushed the structure over the circular tracks, sliding over fifteen trolleys. While Villa Girasole required high energy expenditure associated with its rotational displacement, its heliotropic rationale as a practical means of applying technology to the utilization of natural resources galvanized other experimental solar heating systems and urban architectural designs kinetically adapted to the sun's trajectory (Addis, 2007).

Ultimately, the early twentieth century witnessed vast developments in kinetic architecture. While Futurist and Constructivist rhetoric emblematized architectural kineticism as a symbolic harbinger of the future, parallel developments of the interwar period established kinetic architecture as an actualization of rational means to regulate sunlight, optimize space, or maximize views. This trajectory not only signified an increasingly prevalent allegiance between building and machinery but also overturned traditional ideas of stasis in architecture. In addition to the innovative means of mechanical motility and associated energy integration, this paradigm shift produced new agencies of automatization in architecture. The intensification of mechanical systems in building construction in the form of passenger and freight elevators as well as HVAC equipment required the implementation of automatic, speed-controlling systems. Analog devices such as vertical-shaft flyball governors, provided rudimentary sensory-actuating regulation for adaptable componentry. Operating by means of weights, balls, arms, and links held in tension against the centrifugal action produced by the balls rotating about an axis, the governor provided regulation by translating the angular displacement of the cable (sensor) to activate the governor rope gripping jaws (actuator), clamping it tightly stopping further motion and setting the car safeties automatically without human control (Annett, 1960). Automated devices such as this one engendered the antecedents of adaptable-reactive behavior in architecture - albeit in a localized, basal manner - and foreshadowed the architectural automatization subsequently developed through the emergence of cybernetic theory.

Lineage _ Cybernetics and architectural adaptivity

The emergence of cybernetic theory in the late 1940s brought upon a redefinition to the connotations of adaptation in architecture. The ontogenesis of cybernetics, the interdisciplinary study of the structure of regulatory systems, is credited to Norbert Weiner. In his book, *Cybernetics: or Control and Communication in the Animal and the Machine*, Weiner posits the idea that all systems – biological, cultural and mechanical - each encompass the same principles of feedback. Thus, cybernetic theory developed as an abstract model in order to understand and define the functions and processes of systems in a variety of disciplines. Cybernetics as a specific field grew out of the Macy conferences, a series of interdisciplinary meetings held from 1944 to 1953 that brought together a number of post-war intellectuals. This initiatory cooperative effort developed the syntactical framework of cybernetics by gradually establishing a common language to communicate the intricacies of the various fields present. Furthermore, this consociation underlined an important dichotomy by differentiating between first-order and second-order cybernetics.

The central idea of first-order cybernetics is homeostasis, described as the systemic tendency toward the maintenance of a stable

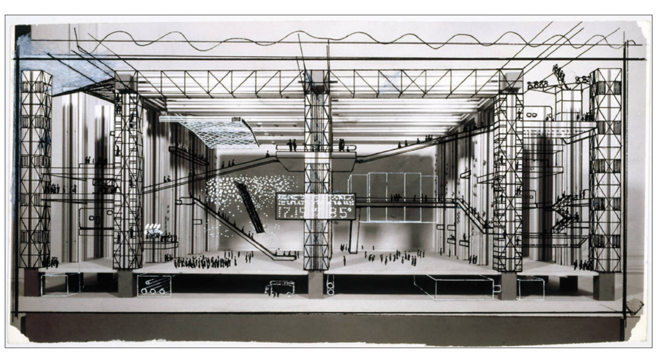


figure 11: *Fun Palace by Pask*

equilibrium. Second order-cybernetics is defined by the additional principle of reflexivity, where the rules that maintain stable equilibrium are recursive, enabling more complex behavior. Reflexivity in a system signifies that regulatory feedback devices are inherently non-neutral and possess properties or 'motivations' that condition the feedback. Second-order cybernetics thus emphasizes the role of the observer in modeling a system and the resulting methodological and epistemological implications to the field as a whole[1].

The incipient convergence of built environments and cybernetic theory originated through Gordon Pask and his pioneering work in understanding and identifying the field of adaptive architecture. Pask, an English cybernetician who collaborated with London's Architectural Association in the 1960s, developed his seminal *conversation theory*, a foundational concept, which served as an essential paradigm of second-order cybernetics postulating that information is reconstructed by constant interaction between entities without pre-identifying the controller and that which is controlled (first-order cybernetics). Rather than an environment that strictly interprets desires, Pask argued that said environment should allow occupants to take a bottom-up role in configuring their surroundings in a malleable way without specific goals. (Fox & Kemp, 2009)

Paskian precepts found countenance in the realm of architectural theory through his 1960s collaborative work with Cedric Price, an English architect. The paradigmatic *Fun Palace* (1961) provided an initial representation of the fusion between architecture and cybernetics. Initiated with Joan Littlewood, the theatre

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1 Katherine N. Hayles, later postulated, in her 1996 work: Boundary Disputes: Homeostasis, Reflexivity, and the Foundations of Cybernetics, a *third* order of cybernetics which extends the concept of reflexivity to contemporary research on self-organizing systems that evolve in unpredictable and complex ways through *emergent* processes.

director and founder of the innovative Theatre Workshop in east London, *Fun Palace* was designed as a *laboratory of fun* with facilities for dancing, music, drama and fireworks. Central to Price's practice was the belief that through the correct use of new technology the public could have unprecedented control over their environment, resulting in a building which could be responsive to visitors' needs and the many activities intended to take place there. Using an unenclosed steel structure, fully serviced by traveling gantry cranes the building comprised a 'kit of parts': pre-fabricated walls, platforms, floors, stairs, and ceiling modules that could be moved and assembled by the cranes. Virtually every part of the structure was variable. 'Its form and structure, resembling a large shipyard in which enclosures such as theatres, cinemas, restaurants, workshops, rally areas, can be assembled, moved, re-arranged and scrapped continuously' promised Price. Although never realized, *Fun Palace* depicted an architecture of process that was indeterminate, flexible and adaptive to the varying needs of its occupants.

In addition to the theoretical framework of adaptive architecture, Price's body of work also extended into the realm of artificial intelligence. His *Generator* project provided an early investigation into artificially intelligent architecture that was designed with no specific program, but only a desired end-effect, in mind. In this context, Price defined intelligence as the capacity of an entity to learn about its environment and develop its own ability to interact with it. John Frazer, a pioneering figure in the use of computers for design who collaborated with Price on *Generator*, extended this idea positing that architecture should be a 'living, evolving thing' (Frazer, 1995). Frazer undertook a series of research projects at the Architecture Association, which culminated in the exhibition *Evolutionary Architecture*. Gordon Pask participated in the projects and wrote the introduction to the book documenting the exhibition, in which he stresses the cybernetic feature of the research. Frazer describes the design research more in terms of a biological analogy.

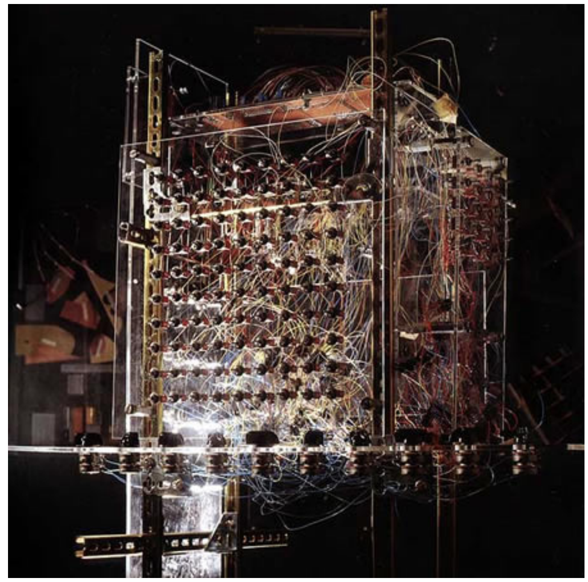

figure 12 : *Evolutionary Architecture by Frazer*

The evolutionary model requires an architectural concept to be described in a form of genetic code. This code is mutated and developed by computer program into a series of models in response to a simulated environment. The models are then evaluated in that environment and the code of successful models used to reiterate the cycle until a particular stage of development is selected for prototyping in the real world (Frazer 1995).

Through design processes and built work, Frazer's *iterative adaptation* scheme hypostatized a computational-biological model for architecture predicated on ideas of evolutionary adaptation. Informed by cybernetics, which identifies similarities in the processing of information in organic and inorganic systems, Frazer proposed architecture as a dynamic system that emerges, mutates and evolves in a non-linear, iterative manner by means of a continuous, interactive dialogue with its environment.

While providing the basis of computational models of evolutionary behavior, biological paradigms also came to inform new rationales for kinetic architecture. In 1970, Zuk and Clark published *Kinetic Architecture*, a manifesto advocating for transformative design not only as an idea of kineticism, but also as a set of architectural strategies requiring new conceptual and material notions of building to take precedent over older, fixed concepts of permanence and monumentality. With its D'Arcy Thompson-inspired rhetoric of formal morphogenesis and descriptions of the multi-variable evolution and adaptation inherent in machines, *Kinetic Architecture* provides a practical design manual on architecture adaptive (via kinetic structural systems), to changing environmental conditions and programmatic needs. Zuk and Clark discuss auditoriums and stadiums with moveable seating and retractable roofs, self-erecting shelters, pneumatic exhibition pavilions, revolving structures, and a variety of experimental and conceptual designs for modular buildings and cities intended to be expanded incrementally. Through their pragmatic examination of adaptable spaces, Zuk and Clark introduce a four-part taxonomy[2] classifying machine technology according to an inherent ability to adapt to differing needs: level 1 machines perform a single operation repeatedly; while level 2 machines can perform multiple functions, either in sequence or simultaneously; level 3 machines are distinguished by automatically adaptive control systems; level 4 machines link the adaptive control system to a processor – this, as conceived in 1970, offered the optimistic promise of architectural machines capable of adapting trough heuristic learning abilities.

Lineage _ Temporality & Aesthetics of Kinetics

In addition to the pragmatic and technological narratives characterizing the lineage of kinetic architecture in the twentieth century, kinetics as an aesthetic idea also pervaded its fabric. Zuk and Clark's *Kinetic Architecture* discusses the need

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2 This classification scheme can be seen as prefiguring the taxonomy of control of Fox and Kemp's *Interactive Architecture* (2009).

for kinetic architecture, hitherto mainly symbolized by pragmatic adaptability, to develop a new aesthetic based on motion and time. Zuk and Clark represent this idea of a temporal understanding of kinetics throughout their examples, as designers conceive kinetics in terms of multiple overlapping rates of change, from daily to yearly horometrical scales.

Since time is the basic measure of motion, it becomes an important factor in design. This suggests that kinetic architecture must be considered as a continuum. The movement unfolds, but what the form has been or what it will be, are a matter for recollection or conjecture. This architecture can never be confronted whole. A definition of form, which is time dependent, must be recognized… The sense of motion, itself, then, can be a visual aesthetic much as has traditionally been the case with basic elements like color, texture and pattern (Zuk and Clark, 1973).

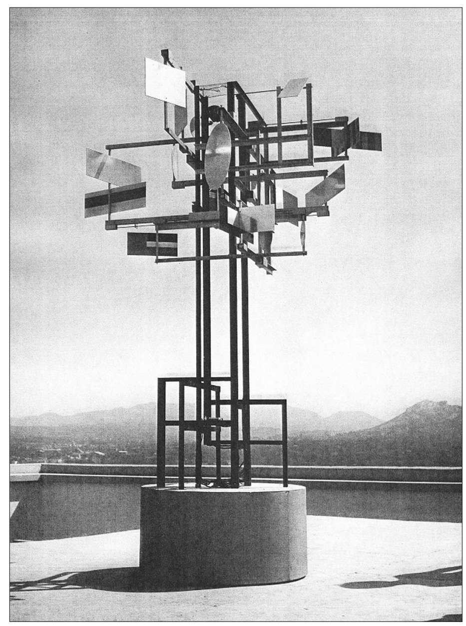


figure 13 : *CYSP 1 by Schöffer*

The notion of an architectural aesthetic predicated on temporality relative to motion resonates with the twentieth century kinetic art. Originating out of the avant-garde experimentation of the early twentieth century, kinetic art explicitly introduced the temporal dimension into art, and explored the potential of motion to transform practice in a range of art forms.

In 1920, Naum Gabo, a prominent Russian sculptor in the Constructivist movement published with Antoine Pevsner the *Realist Manifesto*: ‘We reject the thousand-year-old error, inherited from Egyptian art that sees static rhythms as the only element of visual creativity. We recognize a new element in the visual arts: kinetic rhythms, as basic forms of the perception of real time'. This publication, along with Gabo's exhibition *Virtual Kinetic Volume* provide the platform from which other art forms (painting, sculptures, machine works, and light installations at a range of scales) came to experiment with the phenomenon of movement and its inherent visual possibilities. Beyond this breadth of activity, which achieved its first pinnacle in the work of Moholy-Nagy and experienced a renaissance in the 1960s, a number of artists, critics and historians developed a comprehensive discourse on kinetic art.

In order to supplement Zuk and Clark's initial ideas of aesthetics in kinetic architecture, this section will continue by briefly examining the theoretical framework of kinetic art through Frank Popper's *Origins and Development of Kinetic Art* and George Rickey's *Morphology of Movement.*

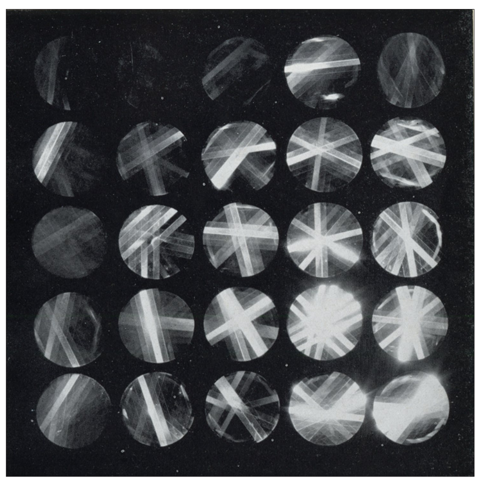


figure 14: *Structure Optique by Padua*

Origins and Development of Kinetic Art, written in 1968 by art historian Frank Popper, serves as a primary reference text on kinetic art providing a comprehensive overview, from the early experiments of Futurism to the high point of kinetic art in the 1950s and 1960s. Popper also establishes a taxonomy scheme distinguishing types of kinetic art, delineating primary classifications as:

- virtual/real
- spatial/non-spatial
- predictable/non-predictable

By means of this categorizing, Popper presents two detailed analyses: a taxonomy based on what he defines as *procedures*; and an overview of aesthetic categories. Popper's emphasis on *procedures* is used to categorize activity used by artists to convey, represent, suggest or introduce movement in plastic arts. Through thirty-one *procedures* grouped into eight categories (figuration, filmic procedures, formal suggestions, movement itself, photographic procedures, precise perceptual suggestions, representation, and various), this rationale underlines the technical, semantic and plastic aspects of movement. The category of *movement itself*, which provides a particular connection with kinetic architecture, further subdivides into this group of *procedures*:

- simple mechanical
- electro-mechanical, electronic, thermal and magnetic
- mobiles
- projections, reflections, refractions of light

Beyond a general alignment with the framework of kinetic architecture, the selected aspects of these procedures[3] inherent in *Origins and Development of Kinetic Art*'s encyclopedic survey that traces movement in impressionism and surrealism, does not produce significant thematic parallels to kinetic architecture. However, Popper does offer insight into the discussion of an aesthetic of movement, in the context of

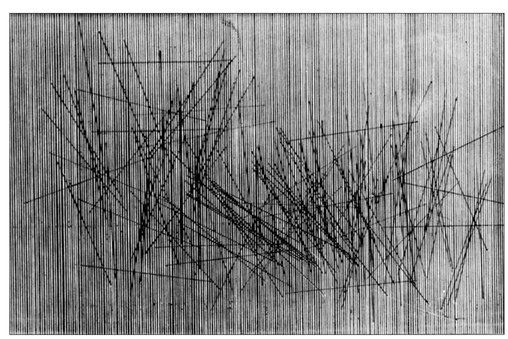


figure 15: *Structures Cinetiques by Soto*

3 This, along with the controllable transformation of material properties – a *procedure* partially in covered in the *various* category - which describes movement through the growth and deterioration of the material.

architecture, by considering two criteria – unpredictability and the *agogic* (Popper, 1968).

Popper describes the notion of unpredictability through his examination of the work of Alexander Calder and Nicolas Schöffer. Popper contends that Calder's mobiles (1932) and other tactics of suspension enable an inherent unpredictability through a delicacy of response to environmental forces. A contrasting approach is also considered through the discussion of Schoeffer and his work in sculpture and cybernetics. Popper scrutinizes CYSP 1 (1956), a reactive sculpture provoking structural changes through audio and lumino-sensors, for its mechanical element of *indifference*. Popper's rationale suggests that a degree of indeterminacy in directed control systems provides an important criterion in the design of kinetic patterning.

The second recurring motif is the examination of temporal scale, which Popper describes in relation to the musical term *agogic*. Musically, this connotes the use of accents to prolong the duration of a note. Popper refers to the work of theorist Etienne Souriau who delineates the *agogic* from rhythm.

In Souriau's view agogic or tempo (with its nuances of andante, adagio, presto, etc.) must be firmly distinguished from the rhythm, which only refers to a certain structural organization of time, generally referred to as a cyclic figure. The agogic also refers to nuances of acceleration (allegro and andante in music) and the category is technically almost impossible to explain – fastness and slowness being simply the response to an impression. Two groups can nevertheless be singled out: values concerned with excitation or incitation, and values connected with appeasement and calm (Popper, 1968).

Souriau describes his notion of the *agogic* as an explicit reaction to the 'rather bland description arts of space in contrast to the phonetic and cinematic arts' (Popper, 1968). Architecture is included in his proposition, although it is based on the perception of static form – for example, the eye being drawn up a tower by articulation of openings and detail. Popper appropriates the term to describe the quality of temporal pattern that he identifies in a range of works. At one end of the spectrum is the elegant slowness and smooth acceleration of George Rickey's counterweight suspensions. At the other is the velocity and dramatic choreography of a Len Lye installation. The term *agogic* thus conflates speed, acceleration and duration and would appear to be a significant aspect of kinetic form (Moloney, 2011).

While Popper's *Origins and Development of Kinetic Art* offers a comprehensive survey of kinetic art, George Rickey's *Morphology of Movement*, is considered one of few definitive theoretical texts engaging with formal dimensions of the discipline of the period up until 1963. Rickey provides thorough analyses of six critical elements pertaining to optical phenomena; transformation based on phenomena such as wheel spokes in motion, or through motion of the observer; works where the surveyor physically interacts with the work; machines where motorized gears and pulleys cause orchestrated movement; light play; and *movement itself*[4]. In movement itself, he argues that kinetic art ought to embody movement such that capacity for motion is intrinsically designed within the artifact, which in turn extends an experience devoid of formal or figurative associations.

Motion is measured by time, of which we all have some rather precise perception. We can compute it, sometimes with uncanny precision, witness catching a ball, passing a car on the highway, or riding a surfboard. We can measure slow-fast,

4 This term *movement itself* stems from The Realistic Manifesto, in which Gabo observes the limits of Italian Futurism as simple graphic registration that cannot re-create movement itself.

long-short, pause, interval, beats per second, period of swing, coming towards us, going away from us, acceleration, vibrations separated, vibrations as a tone – these are all measurable without comparison with other objects or recollections of past experience or relation to other events in time; they have a kind of immediate measure, which, in spite of the abstractness, can have a sense of scale (Rickey, 1963).

Rickey's intuition that motion can be clearly distinguished has been subsequently been proven in medical research, where Zeki and Lamb have determined motion is an autonomous visual attribute, separately processed and therefore one of the visual attributes having primacy, just like form or color or depth. He continues his assertion that the essence of kinetic art is the design of movement, by articulating a range of examples: the classic movements of a ship at sea (pitch, roll, fall, rise, yaw, shear); vibrating springs; the non-periodic movement of a pendulum. For Rickey these are examples of a vocabulary of form in motion, small in number and surprisingly simple, *scarcely more than the twelve tones of western music*. Continuing his analogy, this vocabulary is arranged as sequences over time in a similar manner to musical composition. Rickey differentiates kinetic art from music, in terms of its openness to chance 'introduced by the movement of the observer, which the artist prepares for but does not predetermine, or by incorporating in the object itself, some factor of fortuitousness' (Rickey, 1963).

In contrast to Popper's proliferating sets of procedures, Rickey is focused on what he considers to be essential and differentiating characteristics of kinetic art. Rickey's analogies and critiques of kinetic artworks are not codified in terms of an essential diagram or taxonomy of approaches. Rather, Rickey summarizes a range of activity that is considered under the umbrella term kinetic art, and then rejects all but those that focus on *movement itself*. The idea of *type* of movement is subsequently discussed in relation to form, or what Rickey designates as the *morphology* of kinetic art.

When Roger Fry wrote of significant form he was trying to find a universal equivalent of the distinguishable or identifiable forms of different epochs and cultures –of what Giotto, El Greco, Cezanne and Negro art has in common. His was an idea of form as a discernible factor in a value appraisal. The form referred to in these paragraphs is without immediate aesthetic or quality implications and is closer to style or to the morphology of modern art (Rickey, 1963).

This morphology is summarized as four key principles:

- There are a small number of basic movement types.
- Basic movements combine to produce composite movement.
- Basic and composite movement, in combination with temporal variables produces sequences of movement.
- Sequence may have a spatial dimension, i.e. the sequence may occur in the same location and/or propagate through space.

These axioms provide a basis for describing movement at the scale of a singular part. They reflect Rickey's art practice, which typically consists of small groups of geometric forms, pivoted to allow sequences of composite movement within a fixed spatial location. Based on either variation within the same spatial location or sequence based on propagation through space, Rickey proposes that a kinetic pattern results from the relative movement of individual parts synchronized or offset in time, which produce differentiated clusters of similar movement or propagation of similar kinetic resonance. Rickey's principles of movement sequence provide valuable insight for considering the formation of movement patterns within architecture characterized by multiple kinetic parts (translation, rotation, or scaling): an architectural typology that came into prominence in the 1980s through development of digital computation (Moloney, 2011).

Lineage _ Ubiquitous Computing & Shifting Paradigms

While the 1970s heralded a shift toward a promise of environmental efficiency and building performance brought upon by the prospect of automated kinetic componentry, it was not until the following decade that architecture began to systemically implement computational technologies. The 1980s brought forth important developments in the field of computer science in the form of intelligent environments (IE). Defined as spaces in which computation is seamlessly used to enhance ordinary activity, intelligent environments describe physical environments in which information, communication technologies and sensor systems disappear, as they become embedded into physical objects, infrastructures, and the surroundings. Michael Mozer, who developed the pioneering *Adaptive House*, delineates the intelligence of a building by its ability to predict behaviors and exigencies of its inhabitants through observation sustained over time. As opposed to performing specific, programmed actions, the *Adaptive House* operates by monitoring the environment and sensing actions of user occupancy to in turn learn to prognosticate future states of the house (Fox & Kemp, 2009).

figure 16: *Adaptive House by Mozer*

As wireless networks, embedded processors and sensor effectors became technologically and economically viable to implement, the 1990s engendered a variety of academic IE projects. This viability fuelled new experimentation in adaptive architecture, as many earlier design schemes, previously stifled by the technical and financial obstacles, were now achievable through the prospect of inexpensive computational hardware. This propensity was further substantiated by an increasing impetus to re-examine kinetics in architecture through a lens of performativity, such that physical adaptation of kinetic systems could optimize building functionality in response to dynamic environmental pressures. Through this kind of catalysis, adaptive architecture developed a series of prototypes modulating climatic control, spatial flexibility and functional plurality primarily by means of a mechanistic approach to kinetic systems – through the assembly of intricate, machinal joints, actuators and control components (Kolarevic, 2005).

By the recent agency of interdisciplinary design, adaptive architecture has begun transitioning from a mechanical paradigm of adaptation to one rooted in biological constructs. This biological paradigm 'is intrinsically tied to the performative aspects of the operational scale and the inherent behavior of materials, as well as the role that innovative materials may play in designing and building environments that address changing needs' (Fox & Kemp, 2009). These material advents present an opportunity to integrate adaptation and response in autonomous material systems, able to anticipate environmental forces and respond to them through their material interrelations, and embedded dynamic capability. Likewise in biological systems where properties change through seamless materialities, the focus is not on the articulation of disparate elements but on continuous material systems that, through their intrinsic properties, can anticipate both a stable adaptation towards structural integrity as well as exhibiting dynamic response to extrinsic stimuli (Doumpioti, 2011). Through these integrated processes operating at diminutive granularities, architectural design continues a nascent shift towards the modalities of biological paradigms.

Precedents

As architectural kinetics seeks to develop new means of adaptive behavior by the agency of biological constructs and their transposition into the realm of design, the question becomes: how does architecture kinetically adapt? - and more importantly: how can architectural means of kinetic adaptation interface with those of biological systems? While the previous chapter provided a contextualization of kinetic architecture and its emergence over the last hundred years, this section examines a range of current architectural projects through a technical lens in order to delineate the expanse of kineticism in contemporary architecture. Through this analytical study encompassing the ways in which architectural kinetics are manifest [type of kinetic operation and variability in geometry] as well as the means by which they are realized [mechanical, chemical technologies], this chapter aims to situate the architectural extent of adaptation on a spectrum of kinetic complexity (thus establishing a platform from which to consider the reciprocities with organic systems). This scan through contemporary activity will be selective, identifying key examples and examining the kinetic variability evident or afforded by the project. This starts with the largest scale, that of dynamic structures. It then proceeds to examine in turn the intermediate scale of kinetic screens and concludes with compliant material systems.

Precedents _ Dynamic Structures

In *Interactive Architecture*, Michael Fox introduces a taxonomy of architectural kinetics, which differentiates between embedded, transportable and dynamic structures. The emphasis of this section will exclude embedded structures (kinetic systems at the scale of the entire building, i.e. earthquake dampening), and transportable structures (re-locatable with an inherent capability to be constructed and deconstructed in reverse) and, in turn, focus on dynamic structures: kinetic systems existing within a larger architectural whole but acting independently with respect to control of the larger context (i.e. when a large opening is required in a building envelope). Archetypal examples of dynamic structures include operable domes in sport arenas as well as kinetic wall sections, ranging in scale from aircraft hangars to storefronts.

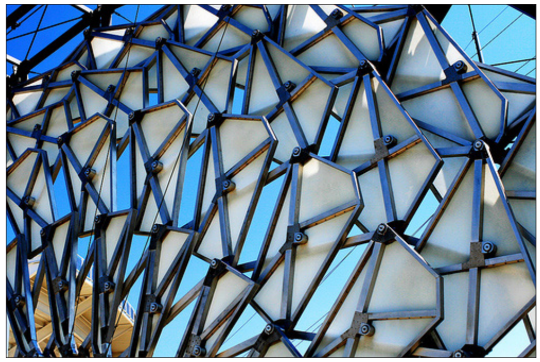


figure 17: *Hoberman Arch*

While Fox provides the principle delineation of kinetic types, Korkmaz (2004) in *An Analytical Study of the Design Potentials in Kinetic Architecture*, offers an exhaustive taxonomy of dynamic structures including soft form buildings (kinetic capacity through tensioned membranes or cable-net pneumatic structures) as well as rigid form buildings (kinetic capacity through deployable, foldable, expandable or rotating and sliding capacity of rigid materials and joint connections). Korkmaz organizes dynamic structures by morphological and kinematic characteristics such that three main groups emerge: spatial bar/plate structures consisting of hinged bars/plates, strut-cable (tensegrity) structures and membrane structures. While dynamic structures are typically conceived and undertaken as engineering solutions, this section will examine architectural examples of each of Korkmaz's categories.

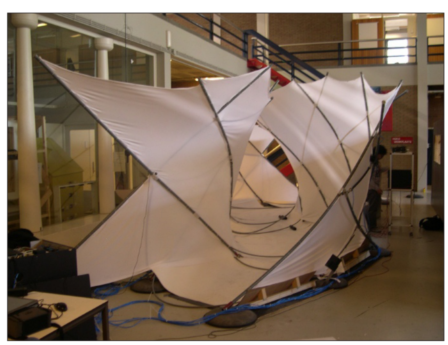


figure 18: *MuscleBody by Oosterhuis*

Firstly, the Hoberman Arch (2002) offers an important example of spatial bar/hinged structures. This structure utilizes scissor joints[5], which produce a singular, incremental motion occurring uniformly across the arch. The work is precision engineered, resulting in a silent, successive folding and unfolding of structural components. The construction of the Hoberman Arch can be considered in two parts: a matrix of movable sections and a structural arch that supports the movable elements. The individual components are made of sandblasted aluminium profiles and 96 translucent fiber reinforced panels. Four different forms are used and fixed in a polysymmetrical, overlapping arrangement so that they enclose the stage entirely when the construction is lowered. The outermost panels are anchored to the structural arch at 13 points; the nodes at the bottom are connected to runners that travel along a rail in the floor from the centre of the stage to the base of the arch as the curtain opens. This lends the lattice construction the necessary structural stability (Schumacher, 2011).

While the Hoberman Arch epitomizes dynamic structures as intricate assemblies of mass-customized pieces, strut-cable (tensegrity) structures are composed of

figure 19: *Responsive Architecture by ORAMBRA*

5 Chuck Hoberman has patented three-dimensional scissor joints, which have been realized as consumer products and at the scale of exhibition works.

repeated modules (tension members and compression members) that form self-stressing structures. This type of dynamic structure is showcased in the work of ORAMBRA through their tensegrity kinetic envelope. This structure consists of a repeated module in which three compression members meet to form *a tripod* whose legs are tethered by tension cables. Repeating this module in a regular pattern, results in the formation of two membranes with variable and controllable rigidity. By controlling the rigidity of these two membranes (through mechanical actuators), the assembly potentiates a structure whose shape can alter. By means of the mechanical action of an actuator, force may be applied to each structural unit in combination, either pulling them towards each other to increase structural rigidity, or pushing them apart to decrease rigidity. Limits to the amount of applied force imposed by an actuator upon a structure are determined by examining the shape of a structure as well as the way in which a structure is required to operate (how much movement is desirable).

The final dynamic structure to be considered is the *MuscleBody* project, a membrane structure project by Kas Oosterhuis and the Hyperbody Research Group. The *MuscleBody* project consists of a full-scale prototype of an interior space. The project is an architectural body that consists of a continuous skin that incorporates all its architectural properties and makes no categorical distinctions such as floor, wall, ceiling, and door. The structure of the *MuscleBody* is based on a single, spiraling tube that is bent in three dimensions. The material properties of the tube, that is normally used as water piping allow for both the needed flexibility and stiffness of the structure. A total of 26 industrial *Festo* muscles are integrated into the spiraling structure to control the physical movement of *MuscleBody*. The skin is further composed of *Lycra*, a stretchable fabric normally used for sports clothing. The translucency of the fabric varies according to the degree of stretching (Moloney, 2011).

While these precedents encompass varying mechanisms of kinetic displacement and means by which they are realized, all three examples of dynamic structures considered can be reduced to one analogous platform of kinetic morphology. Each project exhibits *linearity* in motion: moving from *one* closed condition to *one* open condition and vise versa. This implies that these dynamic structures exist on a one-dimensional kinetic spectrum where morphological variation is restricted to the graduated sequence between the open configuration and the closed configuration. The Hoberman Arch effectively operates reversibly as an iris changing from an open to a closed curtain stage. ORAMBRA's project performs as an actuated tensegrity structure deploying from one folded configuration to an unfolded one. Finally, the *MuscleBody* project, which operates by the agency of a single tube, pulsates more or less uniformly from inflation to deflation under the influence of pneumatic action. While they demonstrate intricacy through sophistication of material assemblies and means of operability, these projects do not particularly exhibit kinetic complexity through means of actuation.

Precedents _ Kinetic Screens

This section moves towards a finer granularity of movement and examines precedents of kinetic screens. This analysis is organized in terms of kinetic type – translation, rotation and scaling – with projects again being selected on the basis of the potential for kinetic range.

While sash and roller mechanisms have been available for centuries to activate external screens, there have been few contemporary indices of translational movement, considered in terms of morphological variability. The *Kiefer Technik Showroom* by Ernst Giselbrecht + Partner epitomizes a substantial example of this type of kinetic architecture. Along the southwest façade of the building, 112 aluminium panels in the form of horizontal folding shutters are mounted on a supporting framework arranged in front of the showroom's glazed façade. The actuation is one of vertical translation incorporated with a folding joint that also enables a scaling effect. When activated along the façade, this allows a range of vertical compositional patterns of translation and scaling. The system is computer controlled, allowing multiple permutations of the vertical stacking motion. As a result, the façade serves not only as a shading function but can also assume a continuously changing appearance that can be choreographed at will.

figure 20: *Kiefer Showroom Technik by Giselbrecht*

figure 21: *WAVE wall by LIGO*

In contrast to translation, there exist a number of kinetic screen precedents employing rotational movement: particularly those equipped with adjustable louvers for the purpose of dynamic sun screening. These kinetic mechanisms typically showcase a uniform and regular adjustment of each bay in relation to sun position. Examples of different approaches to rotational screens include: horizontal orientation as in the case of the Nordic Embassies at Berlin, where each panel is individually controlled and able to be rotated through 90 degrees; vertically, as in the example of the

Malvern Hills Science Park in the UK, where large fins rotate slowly through the day to track the movement of the sun using thermo-hydraulic drives. Finally, the *Wave Wall*, an architectural installation designed for the Laser Interferometer Gravitational-Wave Observatory (LIGO), provides an interesting example dynamic of kinetic range through the coordination of rotational components. This project incorporates rectilinear aluminium sections suspended on low-friction bearings at their centre of gravity, each equipped with embedded electromagnets. Motion is dependent on wind but can also be instigated or dampened by controlling the magnetic strength of singular members, which can also be transferred to adjacent members. This project was commissioned by the science museum to enable the deliberate investigation of patterns related to electromagnetic fields and physical behavior.

In comparison to rotational transformation, there are relatively few precedents based on scaling operations. Most examples of expansion and contraction are found in elastic membranes. Typically, these operate at the scale of pneumatic structures, such as the aforementioned *MuscleBody* project. The *Institut de Monde Arabe*, by Jean Nouvel is perhaps the most famous example of a kinetic façade incorporating scaling transformations. The building's south façade is composed as a grid of 240 square bays where each of these consists of a central circular shutter set within a grid of smaller shutters, referencing the geometry of traditional Arab screens. In this example, the kinetic definition becomes somewhat ambiguous, as the actual movement is one

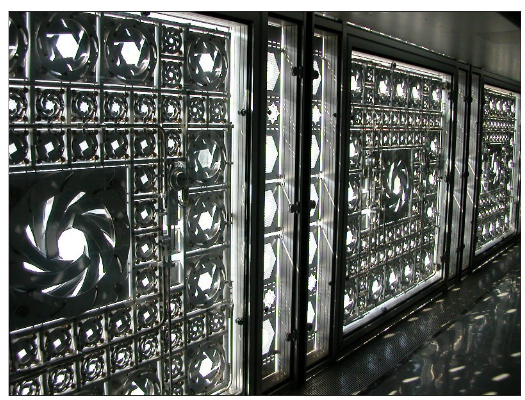


figure 22: *Institut du Monde Arabe by Nouvel*

of rotation of flat sheets over each other, similar to the mechanism of a camera lens. But as the rotational axis of the planar blades are perpendicular to the facade, the kinetic is perceived as a radial scaling kinetic. The expanse of the façade allows for multiple kinetic readings: the kinetic within each bay is one of simple multiple contractions and expansions; while as each bay is individually controlled, the overall composition allows a rich tapestry of kinetic oscillation between bays (Schumacher, 2011).

From a standpoint of kinetic variability, kinetic screens provide greater complexity than their dynamic structure counterparts. Albeit singular modules inherent in kinetic screens operate through sequential linearity (oscillating from one configuration to a second configuration, described in the previous section), it is through a synchronized array of these kinetic devices that a seemingly greater kinetic complexity is achieved. This type of kinetic pattern, as describes in Rickey's *Morphology of Movement*, results from the relative movement of individual parts orchestrated or offset in time, which produce differentiated clusters of similar movement or propagation of similar kinetic resonance. Although this synchronization achieves a greater kinetic complexity, it must be emphasized that each module is physically independent from the rest of the array, such that its morphology depends on those of other modules only by the agency of computational control. Although visually there appears to be dynamic interaction between modules and a systemic tendency toward the maintenance of a stable equilibrium, it is entirely a product of directed, digital mediation rather than one of material interrelations.

Precedents _ Compliant Material Systems

This section examines architectural precedents incorporating the use of polymeric materials in the frame of kinetic systems. The emergence of soft, form-changing material systems has precipitated new, non-mechanical means of affecting physical transformation, namely through passive material systems of variable elasticity and through shape-memory materials and their combinatorial properties. Compliant material systems are characterized by their ability to undergo phase transition without losing their physical state when an input of thermal energy or electrical current acts on them. This is achieved through a two state molecular re-arrangement: a relatively soft and deformable state (martensite) and the more rigid one (austenite). The two states, which can be pre-set by the designer, define the multiple shape changes in between, related to direct temperature differentials. The material can bend and straighten, twist and untwist (nitinol alloys), contract and expend (flexinol alloys).

The work of Philip Beesley provides important architectural precedents of kinetic actuation through the appropriation of shape-memory alloys. *Hylozoic Soil* implements a distributed sensor network driven by dozens of microprocessors, in turn generating the peristaltic movement of kinetic valves thus signaling the presence of occupant interaction. The structural core of *Hylozoic Soil* is a flexible meshwork assembled from small acrylic chevron-shaped tiles that clip together in tetrahedral forms. These units are arrayed into a resilient, self-bracing diagonally organized space-truss. In addition to *whisker elements* driven by DC motors, *Hylozoic Soil*'s means of kinetic

figure 23: *Hylozoic Soil by Beesley*

operability is accomplished through its *breathing* and *kissing* mechanisms actuated by shape-memory alloy *muscle* wire. *Breathing pores* are composed of thin sheets shaped into outward branching serrated membranes, each containing flexible acrylic tongue stiffeners fitted with monofilament tendons. The tendons pull along the surface of each tongue, producing upward curling motions that sweep through the surrounding air. *Kissing pores* use a similar mechanical structure fitted with a fleshy latex membrane and offer cupping, pulling motions. A *swallowing* pore occurs in a triangular layout that creates a dense series of openings running throughout the meshwork. These openings contain pivoting arms in triangular arrays that push out radially against the surrounding mesh, producing expanding and contracting movements (Beesley, 2006).

figure 24: *Open Columns by Khan*

A second prominent example of kinetic actuation through compliant materials is Omar Khan's *Open Columns*: a system of composite urethane elastomers columns. They can be deployed in a variety of patterns to reconfigure the space beneath them. These patterns create gradations of enclosure, either in plan through the full deployment of columns, in section through their partial unfurling to change ceiling heights or through a combination of the two. *Open Columns* exhibits a capacity to adapt through the material composition of urethane polymer and its unique quality of variable hardness. By blending different hardnesses together into more complex composites, the structure's elasticity could be better calibrated for particular performance while also increasing variety in the overall structure. Depending on the size of the column array and its formation the system is able to create subtle to stark variations of spaces according to preprogrammed scenarios or through real time sensor based responses (Khan, 2008).

The third polymeric material to be considered is Manuel Kretzer's *ShapeShift*. This project explores the potential application of electro-active polymers (EAP): an ultra-lightweight, flexible material with the ability to change shape without the need for mechanical actuators. EAP is a polymer actuator that converts electrical power into mechanical force. In principle it consists of a thin layer of very elastic acrylic tape sandwiched between two electrodes. Once the voltage in the range of several kilovolts is applied between the electrodes, the polymer changes its shape in two ways. First, due to the attraction of the opposing charges, the film is squeezed in the thickness direction (up to 380%); secondly, the repelling forces between equal charges on both electrodes result in a linear expansion of the film. As a result, due to the initial pre-stretching of the acrylic film, the frame bends and after application of voltage, the material expands thereby flattening out the component (Kretzer, 2011).

figure 25: *Shapeshift by Kretzer*

The emergence of compliant material systems constitutes an important shift from the conventional modalities of kinetic architecture, hitherto delineated by hard mechanical means. *Soft* material technologies potentiate new paradigms of flexibility and lightness for architectural kinetics as they allow for increasingly complex geometries, reduced transportation costs, and increased ease of construction. From a standpoint of kinetic complexity though, the integration of polymeric materials systems in architecture still finds itself in the incipient stages of developing beyond the paradigms of linear movement, as described through precedents of dynamic structures and kinetic screens. For example, while Beesley's *Hylozoic Soil* has engendered unusual and beautiful manifestations of architectural kinesis through the employment of SMAs, such as the curling motion of its acrylic tongues, these light and flexible devices operate on a linear spectrum of motion encompassed by the sequence between one open configuration and one closed configuration. Khan's *Open Columns* also exemplifies a linearity of motion in its deployment configurations despite the sophistication of its material assembly.

Conversely, Kretzer's *ShapeShift* project showcases an important example of compliant materials and their engagement with kinetic complexity. While this project epitomizes similar characteristics of flexibility and lightness as the Beesley and Khan works, *ShapeShift* potentiates morphological variability where each component has an influence on the form and movement of its neighbors, and therefore, on the structure as a whole. In turn, *Kretzer's* project transcends the expanse of one dimensional linearity characterized by the kinetic precedents considered and engenders a two-dimensional, *matricial* linearity brought upon by networks of material interrelations and nested influences of kinetic effect. Mathematically, this suggests a dynamical system of greater complexity where two fixed rules (instead of one) describe the time dependence (describing what future states follow from the current state) of a point in geometrical space, or its trajectory. While *ShapeShift* exemplifies, albeit in an incremental manner, greater morphological variability, it constitutes a simple, linear dynamical system in contrast to biodynamical systems, which exist as multi-ordered, hierarchical entities exhibiting high integrative levels of organization, and in turn are too complex to understand in terms of individual trajectories.

Biodynamics

In *Scale Matters More than Matter* (2012), Chris Salmaan discusses the appropriation of polymeric materials system and the challenges resulting from the discrepancies of biology and design pertaining to scale, hierarchy and complexity. He cites various biological models existing as complex, hierarchical structures: a nested architecture grown from the bottom-up. He describes the fabrication of these biological examples as an approximate outcome of a process of self- assembly. The process is guided by instructions stored in the genes and constrained by a range of external factors, such as temperature, mechanical loading and the supply of water, light and nutrition. Salmaan believes that architects will have to wait a long time before they can design on the nano-level since in contrast to the subtle 'bottom-up' growth of biological systems, the blunt 'top-down' fabrication of polymeric systems has yet to engage with critical dimensions of growth, adaptation to changing conditions.

In turn, with the aim of meaningfully engaging with mechanisms of biological adaptation, should architectural design side-step the complexities of cellular processes and examine other modalities of biokinesis – ones with congruent models of dynamism to those of architectural kinetics - such as biomechanical principles? While the field of biomechanics does not explicitly interface with bottom-up processes such as growth or self- organization, it provides a tangible model of kinetic effect operating on collateral platforms of scale and assembly to the framework of mechanistic systems of architecture. The following chapter will thus briefly introduce concepts of musculoskeletal dynamics in animal locomotion with the aim of developing transposition strategies between biodynamics and architectural kinetics.

In the majority of vertebrates (fish, insect, amphibian, mammal, reptile, bird) of the Chordate phylum, musculoskeletal interactions (muscle, connective tissue and bone) provides a predominant means of kinetic actuation in the maintenance of body position and the production of controlled, precise movements. The mechanism of force generation in voluntary contraction, responsible for free body movements originates from striated muscle tissue. The process of kinesis of individual striated muscle cells is described through the sliding filament theory in which myosin performs as a molecular motor acting like an active ratchet. Chains of actin proteins form high tensile passive thin filaments that transmit the force generated by myosin to the ends of the muscle. Myosin also forms thick filaments. Each myosin travels along an actin filament repeatedly binding, ratcheting and letting go, sliding the thick filament over the thin filament (Rassier, 2010).

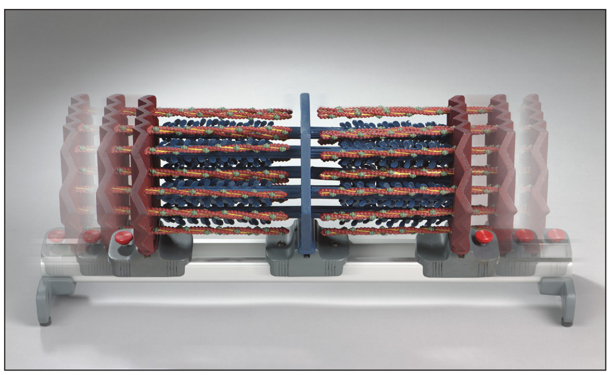
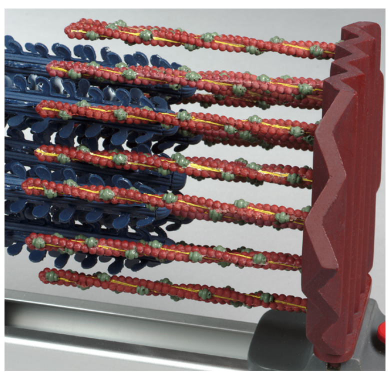


figure 26: Sarcomere Isotonic Contraction

The basic unit of organization of contractile proteins in striated muscle cells is called the sarcomere. It consists of a central bidirectional thick filament flanked by two actin filaments, orientated in opposite directions. When each end of the myosin thick filament ratchets along the actin filament with which it overlaps, the two actin filaments are drawn closer together. Thus, the ends of the sarcomere are drawn in and the sarcomere shortens. Sarcomeres are connected by so-called Z lines, which anchor the ends of actin filaments in such a way that the filaments on each side of the Z line point in opposite directions (with reversed polarity). By this means, sarcomeres are arranged in series. When a muscle fiber contracts, all sarcomeres contract simultaneously so that force is transmitted to the fiber ends.

This muscle contraction is stimulated by the motor neuron relaying an electrical signal to the muscles from the somatic nervous system. Depolarization of the motor neuron results in neurotransmitters being released to the neuromuscular junction, the space between the nerve terminal and the muscle cell. These neurotransmitters diffuse across the synapse and bind to specific receptor sites on the cell membrane of the muscle fiber. When enough receptors are stimulated, an action potential is generated and the muscle cell contracts (Klette, 2008).



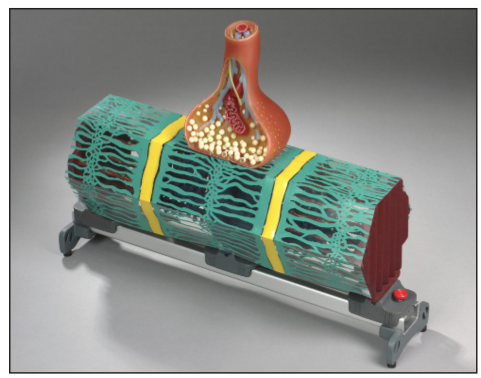


figure 27 + 28*: Actin-Myosin Ratchet & Neuromuscular Junction*

Striated muscle tissue operates by applying tension to their points of insertion to bones. Muscles generate force through contraction; in turn tendons transfer it to bones; and the bones move providing enough force is transmitted. The bones form different types of lever systems. The interaction of muscles, bones (and joints) to generate movements forms a biological lever. A lever is a rigid structure transmitting forces by turning at a fulcrum, in this case a joint. The muscles supply the force that moves the levers. The product of the force that the muscle exerts (F) and the length (or Distance) of its bone- lever (D) equals the torque (T) produced: T = FD.

Levers are classified by first, second, and third class, depending upon the relations among the fulcrum, the effort, and the resistance. First-class levers are characterized by muscle force and resistive force acting on different sides of the fulcrum e.g. the head resting on the vertebral column of bilateral vertebrates. As the head is raised, the facial portion of the skull is the resistance, the fulcrum is between the atlas and occipital bone, and the effort is the contraction of the muscles of the back. Second-class levers are characterized by muscle forces and resistive force acts on the same side of the fulcrum, with the muscle force acting through the level longer than that through which the resistive force acts - e.g. plantar flexion where the body is the resistance, the hind foot is the fulcrum, and the effort is the contraction of the crus of the lower leg muscle. Third-class levers are characterized by muscle force and resistive force acting on the same side of the fulcrum, with the muscle force acting through the lever shorter than that through which the resistive force acts - e.g. adduction of the femur. The weight of the thigh is the resistance, the hip joint is the fulcrum, and the contraction of the adductor muscle is the effort. Beyond biological levers, certain musculoskeletal connections operate through the pulley principle, which changes the direction of an applied force. – e.g. the patella (kneecap), altering the direction in which the quadriceps (patellar) tendon pulls on the tibia (Kumar, 2004).

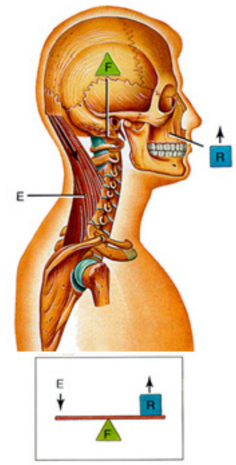


figure 29: *First Class Lever*

figure 30: *Second Class Lever*

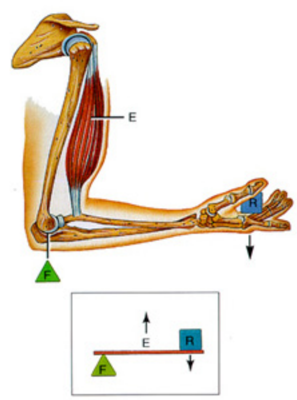


figure 31: *Third Class Lever*

Muscles play four roles in producing joint movements: agonist (prime mover), antagonist, synergist, and fixator. A given muscle can play any of these roles, often moving from one to the next in a series during an action. Agonists and antagonists are opposing muscles such that when an agonist creates tension, the antagonist produces an opposing tension, thereby contributing to control at the joint. A synergist is a kind of muscle that performs, or helps perform, the same set of joint motion as the agonists. Synergist muscles act on movable joints. Synergists are sometimes referred to as neutralizers because they help cancel out, or neutralize, extra motion from the agonists to make sure that the force generated works within the desired plane of motion. A fixator is a stabilizer that acts to eliminate the unwanted movement of an agonist or prime mover's. Fixators steady the proximal end of a limb while movement occurs at the distal end – e.g. the scapula is a freely

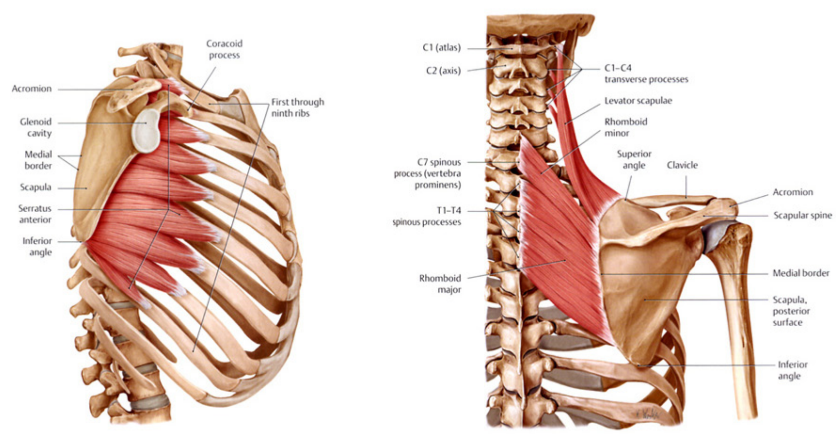


figure 32: *Scapular Fixators | Trapezius - Rhomboids Agonism*

movable bone that serves as the origin for several muscles that move the arm. When the arm contracts the scapula, it draws the radius and the scapula together. Fixators prevent the movement of the scapula, such that the trapezius and rhomboids work isometrically to keep the scapula from moving on the torso (Kumar, 2004).

Animal locomotion arises from complex interactions among sensory systems, processing of sensory information into patterns of motor output, the musculo-skeletal dynamics that follow motor stimulation and the interaction of appendages and body parts with the environment. These processes conspire to produce motions and forces that permit complex manoeuvres with important ecological and evolutionary consequences. Thus, the propensity for physical adaptation to contextual pressures (habitats that animals may exploit, their ability to escape predators or attack prey, their capacity to manoeuvres and turn, or the use of their available energy) depends upon the processes that determine locomotion. How movement is orchestrated and the factors that contribute to control systems employed by animals are central issues surrounding studies of animal locomotion. Similarly, the organization and properties of locomotory structures are important for an animal's physical interaction with its environment and are likely to influence the control strategy it uses to guide its movement (Kumar. 2004).

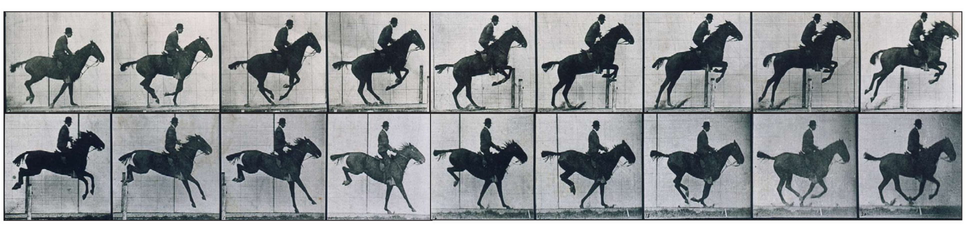


figure 33: *Kinematic Studies by Muybridge*

Recent research suggests that the nervous system controls muscles by activating flexible combinations of muscle synergies to produce a wide repertoire of movements. Muscle synergies are like building blocks, defining characteristic patterns of activation across multiple muscles that may be unique to each individual, but perform similar functions. The identification of muscle synergies has strong implications for the organization and structure of the nervous system, providing a mechanism by which task-level motor intentions are translated into detailed, low-level muscle activation patterns.

The muscle synergy hypothesis has been suggested as a solution to the degrees of freedom problem faced in motor control: instead of having to control many thousands of motor units or dozens of muscles, using muscle synergies the central nervous system can produce behavior by the control of a much smaller number of variables. Another interpretation of muscle synergies is that they provide a translation between task level goals and execution level commands that are necessary to accomplish those goals. In this interpretation, synergies identify the relevant muscle groupings that, when activated together, allow for simplified control of particular biomechanical features of the limb (such as global limb angle or orientation). This interpretation places muscle synergies as part of a hierarchical control strategy, providing a means of organizing both complex motor control variables and sensory feedback so that they can be controlled and interpreted in a task relevant manner.

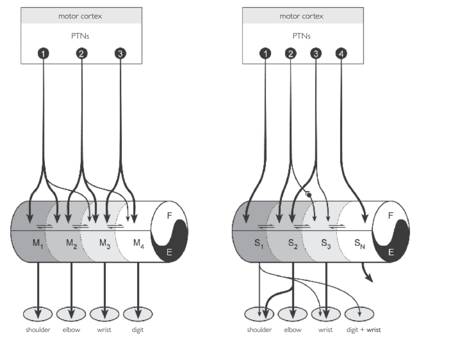


figure 34: *Muscle Synergies-Variable Patterns of Activation*

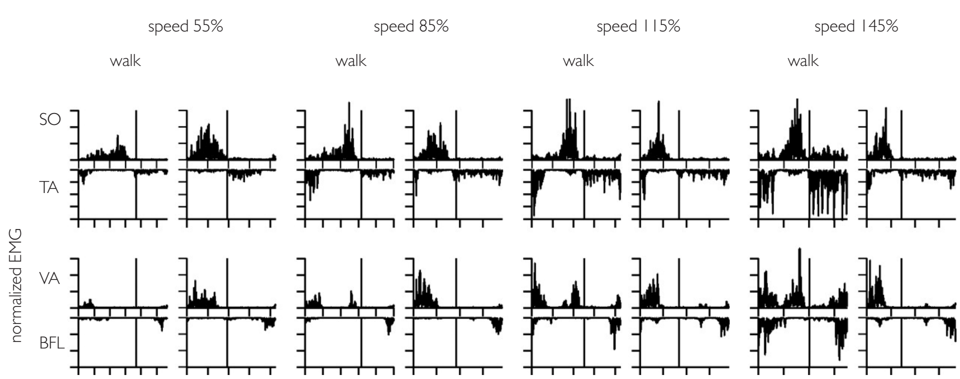


figure 35: *Walk vs. Run | Synergistic Actuation Based on Variable Neuromuscular Trigerring*

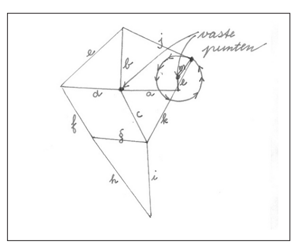
From a design standpoint, the coupling of synergistic motor actuators (sub-components) for the purpose of producing a variety of limb movements (components) provides novel insight into the realm of kinetic architecture. As described in the previous chapter, the framework of transformative architectural components has hitherto been delineated by independent, one-dimensional indices of morphology and limited examples of multi-dimensional kineticism. By extrapolating ideas of synergistic biomechanics, described through the multiplexing of networked kinetic actuators (thereby producing a greater global variability than the sum of its parts), this would provide a conceptual platform from which architectural kinetics could develop novel patterns of movement. By the physical coupling of a small number of interdependent, kinetic effectors (sub-components), it is hypothesized that the overall kinetic component would yield a greater quota of kinetic variability through the synergistic actuations of its subcomponents. Analogous to the muscle synergy hypothesis, this organization would provide a greater complexity of kinetic behavior by the control of a small number of variables, which in turn would imply greater physical adaptation over a decrease in energy expenditure.

The implementation of these ideas was initially explored in this thesis through the study of Theo Jansen's self-propelling mechanical animals. His design for artificial walkers with planar linkage mechanisms designed to simulate a smooth walking motion from a simple rotary motion, provided a valuable model to understand the kinematic effects of linkage variability in locomotive systems. Although the Jansen linkage does not convey an accurate representation of locomotion in any biological organisms in terms of mechanics, it did provide a categorical model from which one can investigate synergistic actuation of effectors.

Design Charrettes

Design experimentation consisted primarily of recreating the leg system of *Strandbeest* through the parameterization of the linkage system:

- 8 links per leg.
- 120 degrees of crank rotation per stride.
- Step height is primarily achieved by a parallel linkage in the leg that is folded during the cycle, angling the lower portion of the leg.



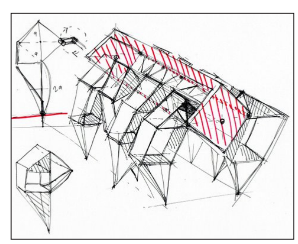


figure 35 + 36 + 37: *Strandbeest by Jansen*

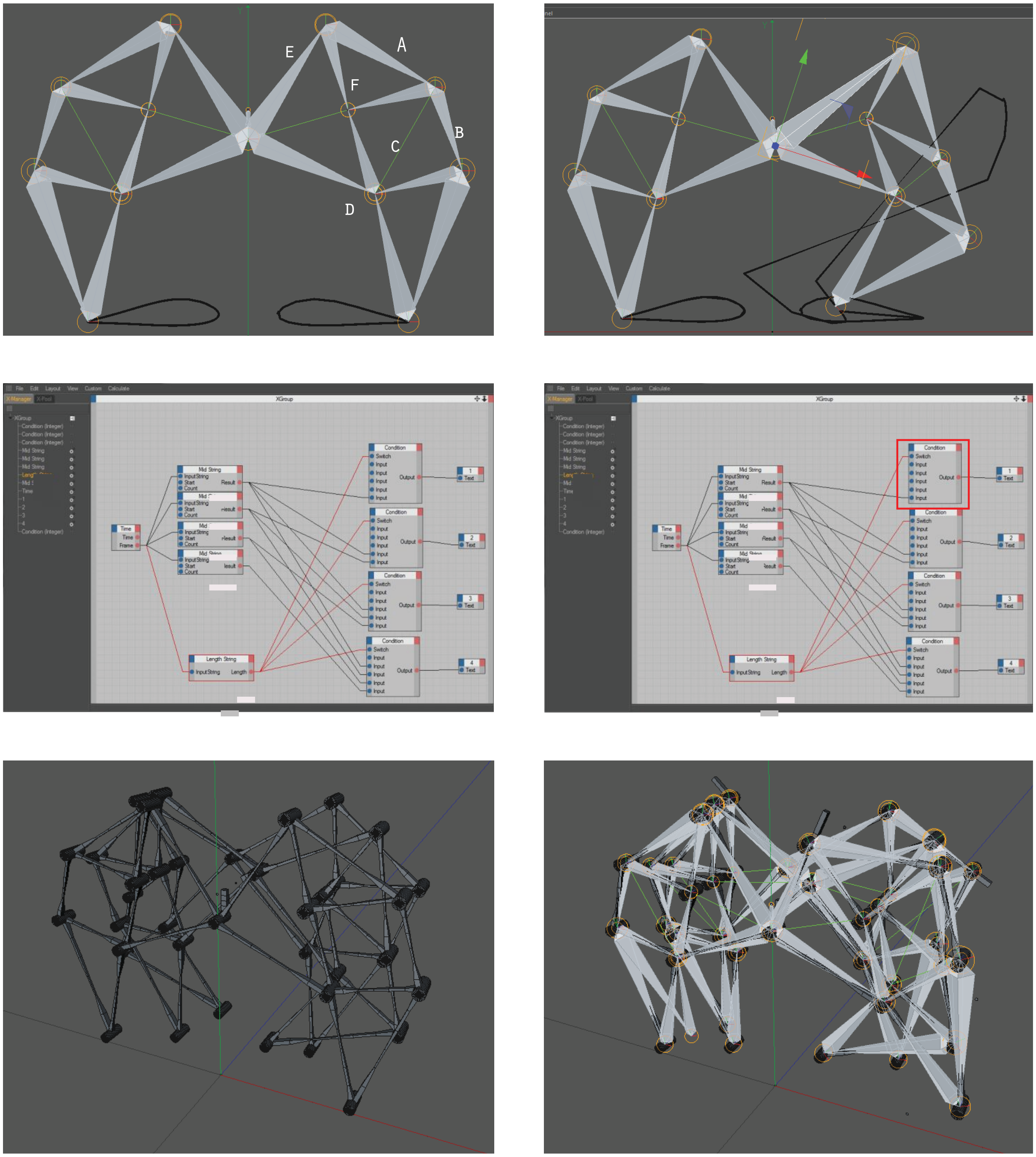


figure 39: Jansen Experiments. Parametrization in Cinema 4D

Design experiments consisted of varying lengths of various limb components (local), and studying the impact of displacement in the overall system. Through combinations of incremental changes to limb lengths, a multitude of kinetic behaviours were created.

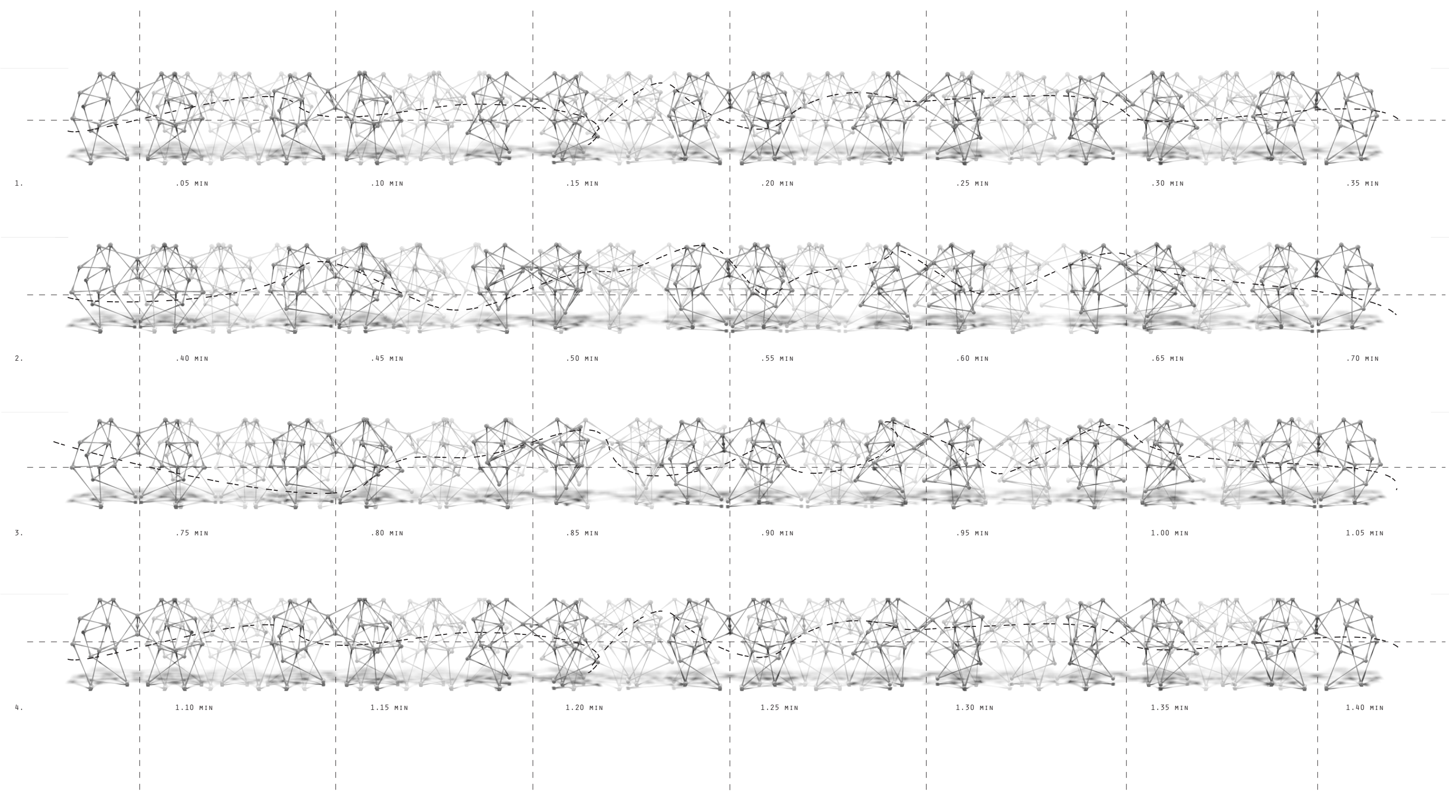


figure 40: Jansen Experiments. Kinematic Studies

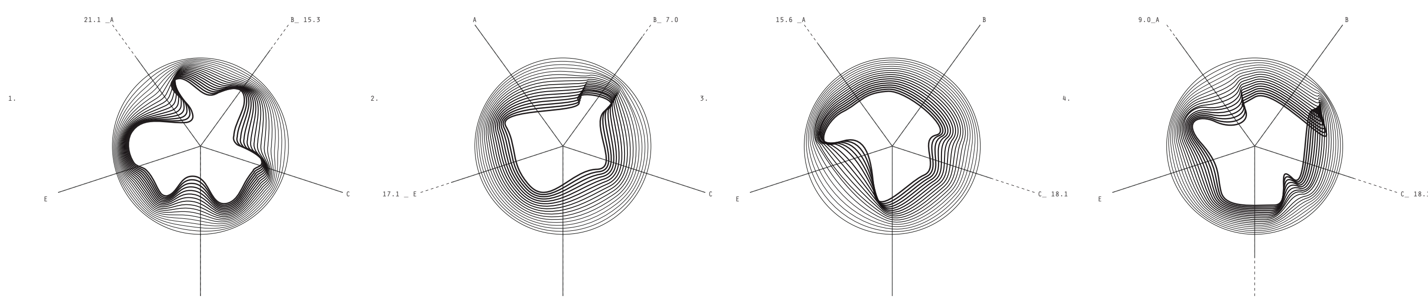


figure 41: Jansen Experiments. Data Mapping

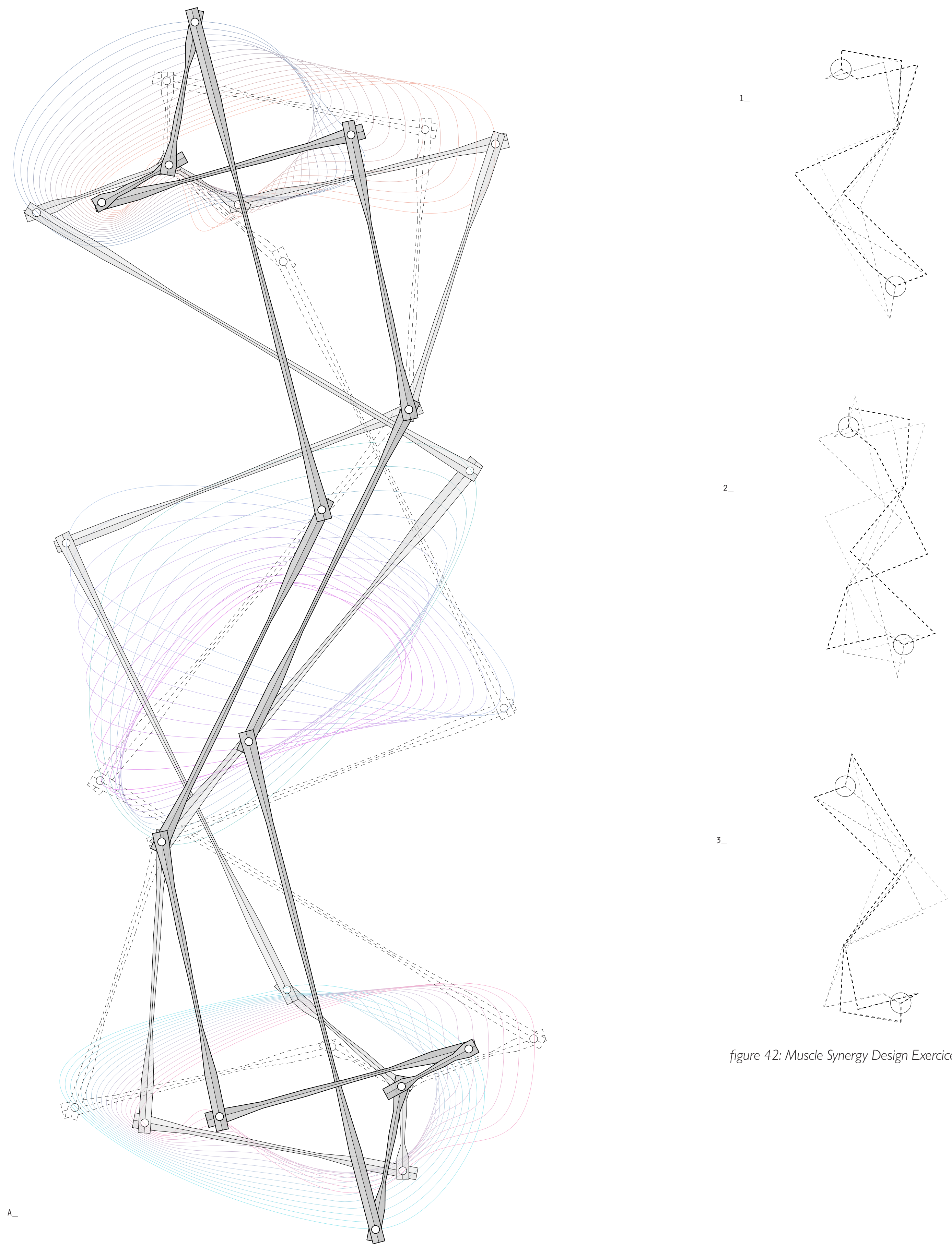
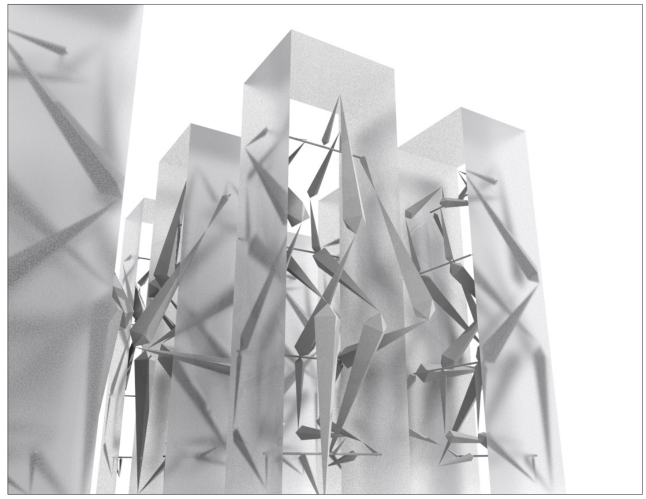
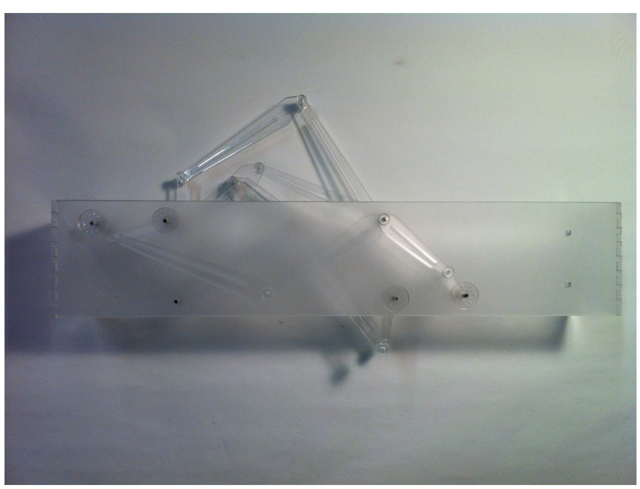


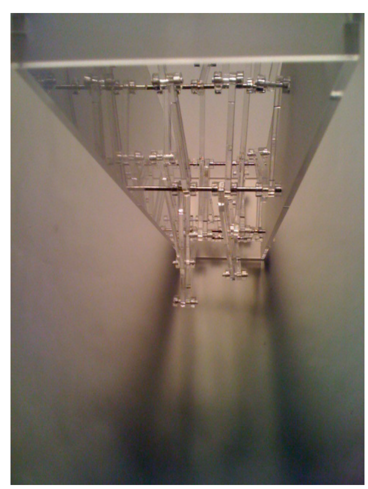
figure 42: Muscle Synergy Design Exercices



The idea then became to fabricate a similar linkage mechanism which could exhibit morphological variability and be used in an architectural context. In this particular design iteration, global movement was driven by an angular actuator while local linkages could vary through linear translation. The outcome of this experiment produced interesting results however it was made apparent that the coupling of acrylic members was problematic. Even with the high precision fabrication techniques (laser cutter), the linkage assemblies produced seizing and uneven angular motion.

figure 43: Muscle Synergy Design Exercices





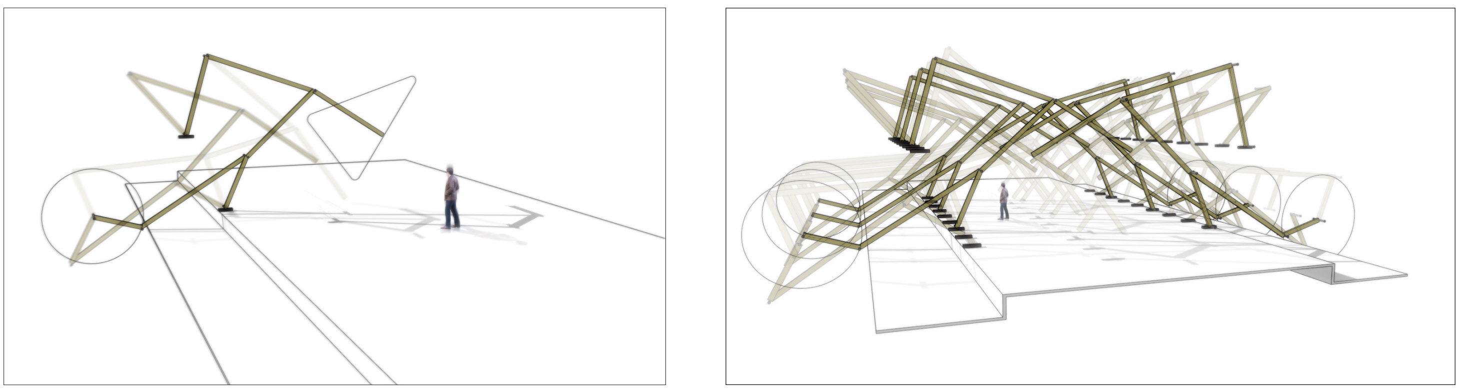


figure 44: Muscle Synergy Design Exercices

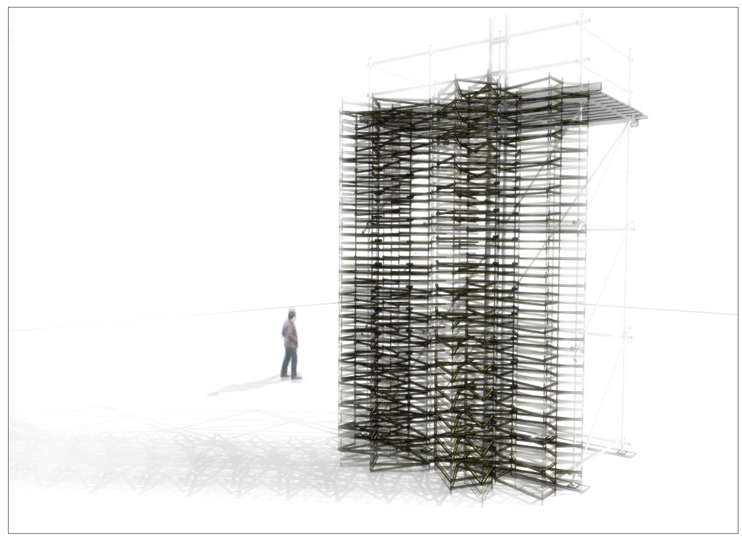


figure 45: Muscle Synergy Design Exercices

In order to circumvent the difficulties in compositing multiple mechanical systems, the ensuing set of design experiments focused on polymeric materials and their potential as embedded kinetic systems working in concurrence with mechanical actuators. Due to their pliant characteristics, it was hypothesized that soft materials would facilitate the integration of a secondary actuator, thereby creating an applicative model for a multiplexed kinetic assembly.

The research and formal experiments culminated with a design aimed to synthesize findings on biomechanics and pliant material systems in order to develop an architectural kinetic prototype embodying greater kinetic complexity than of those examined in precedents research. The kinetic module design consisted of:

- A mechanical actuator driven by pneumatic action, deploying a tensile membrane.
- Shape memory polymers (SMP) driven by resistive heating.
- A secondary SMP system nested in the mechanical actuator, thereby providing matricial dynamic interaction.

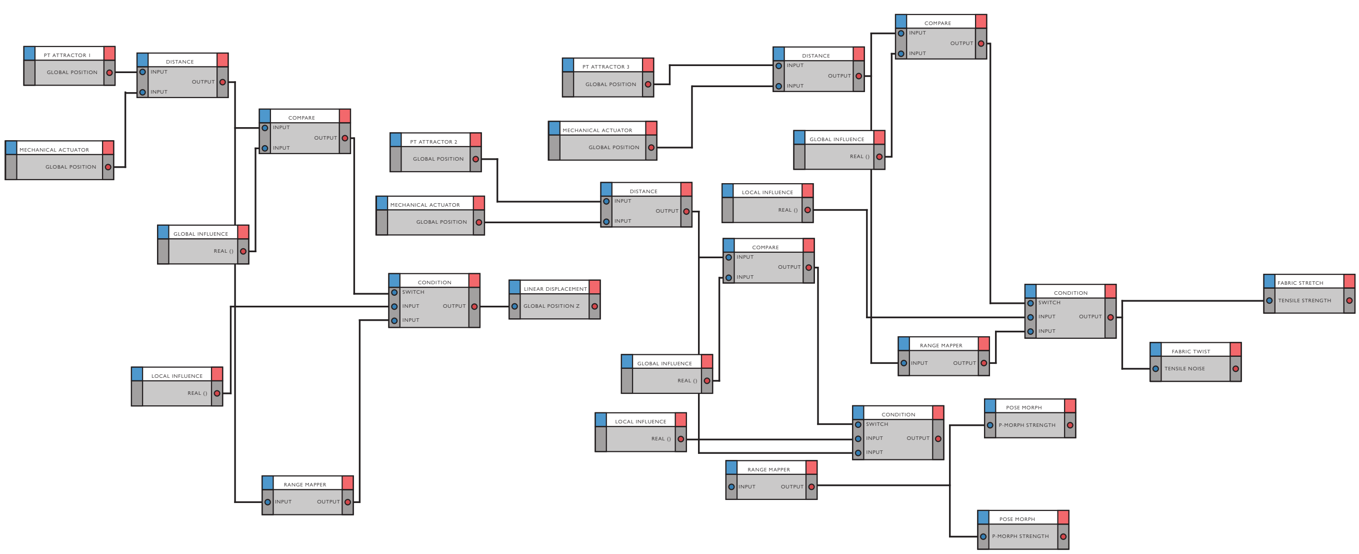


figure 46: Re-creating Physical Conditions through Parametrics-Dynamics Engine

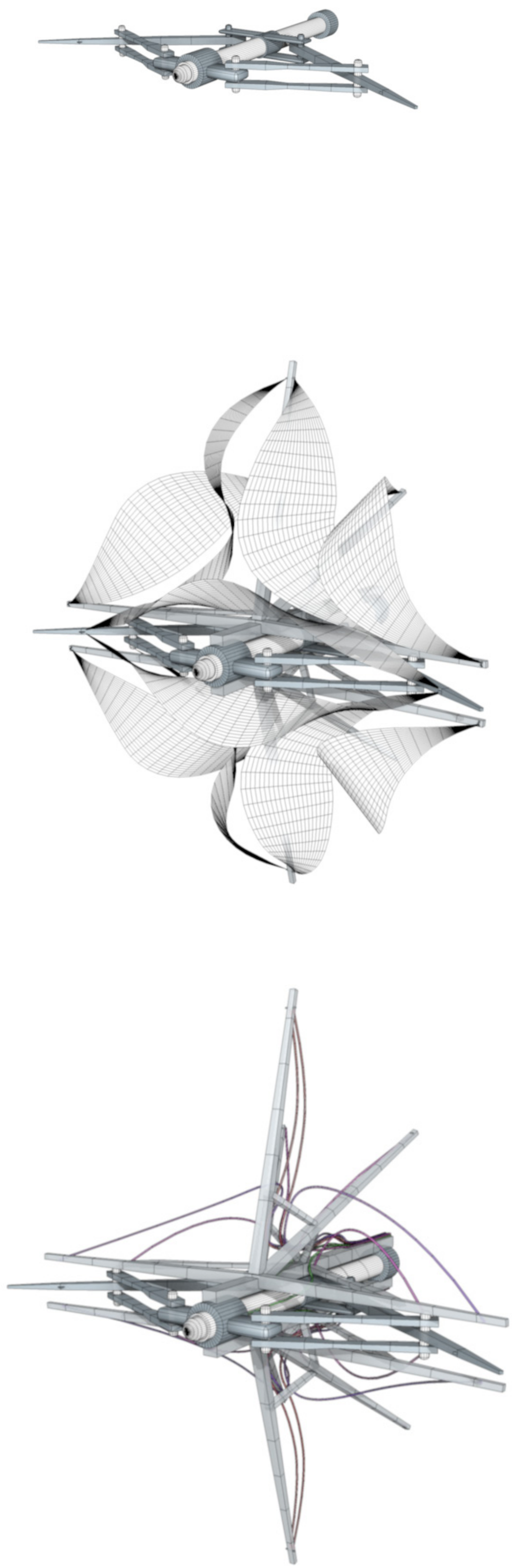
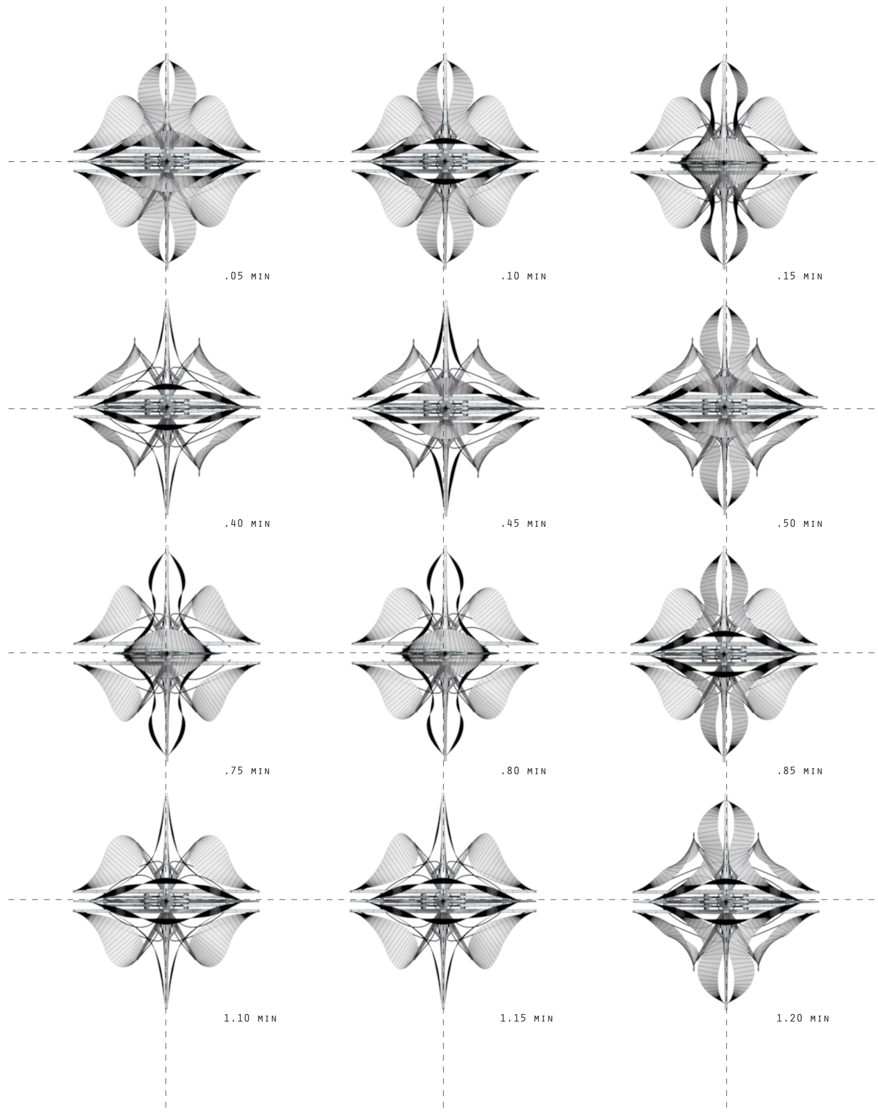


figure 47: Kinetic Component



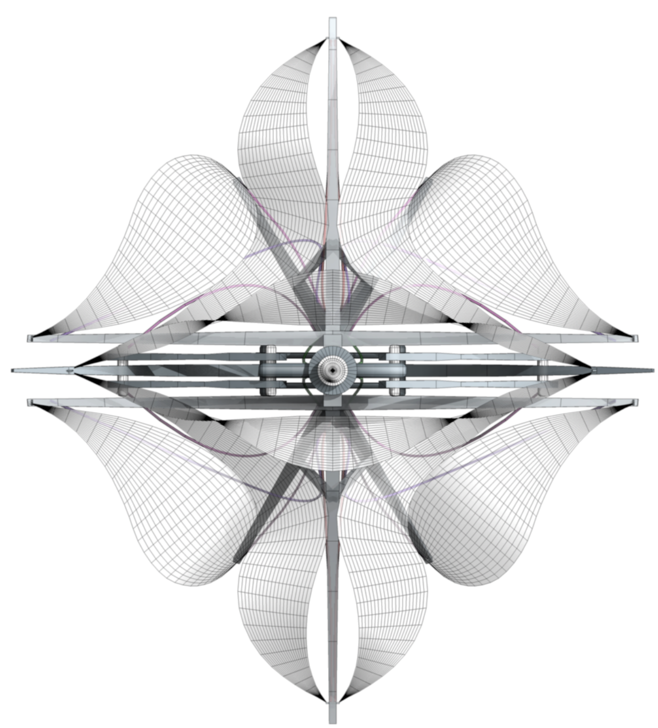


figure 49: Kinetic Component

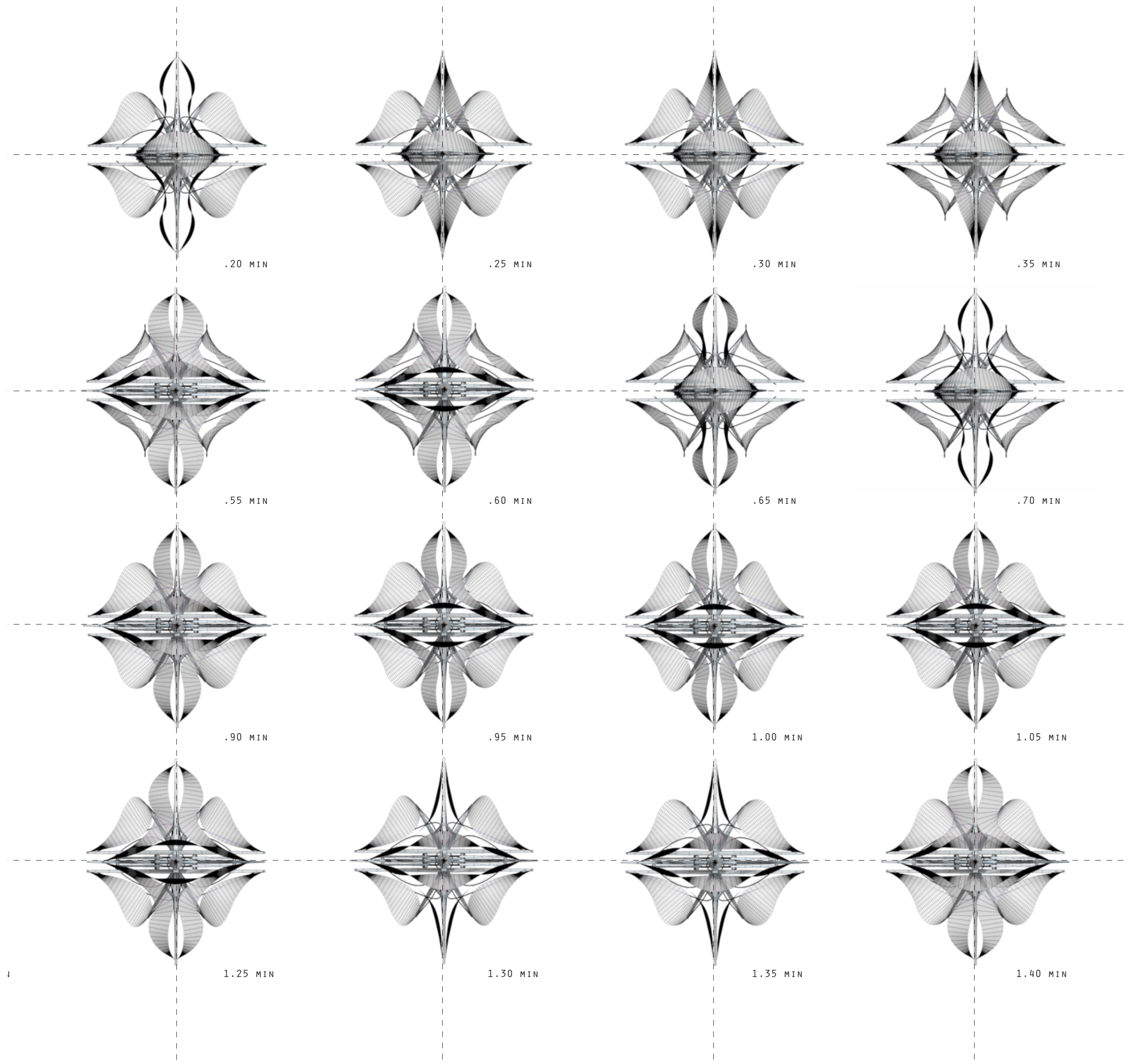
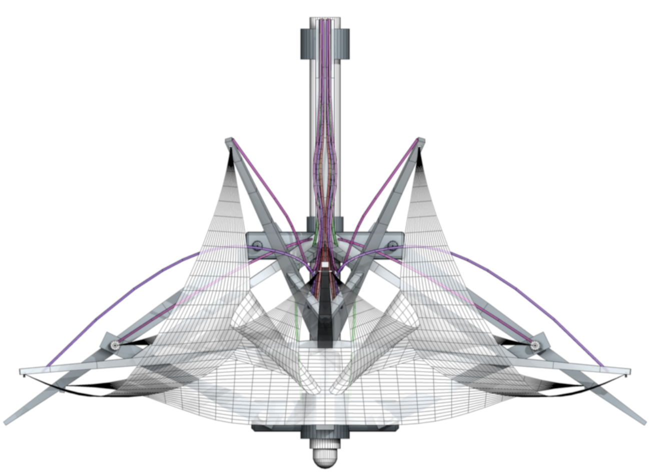
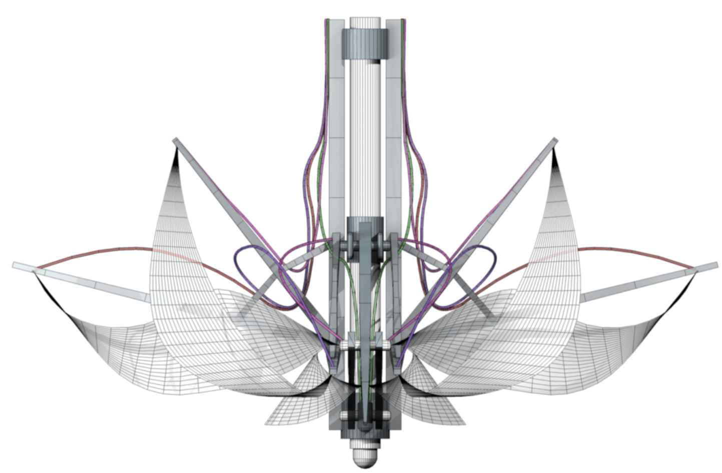


figure 48: Variability Matrix





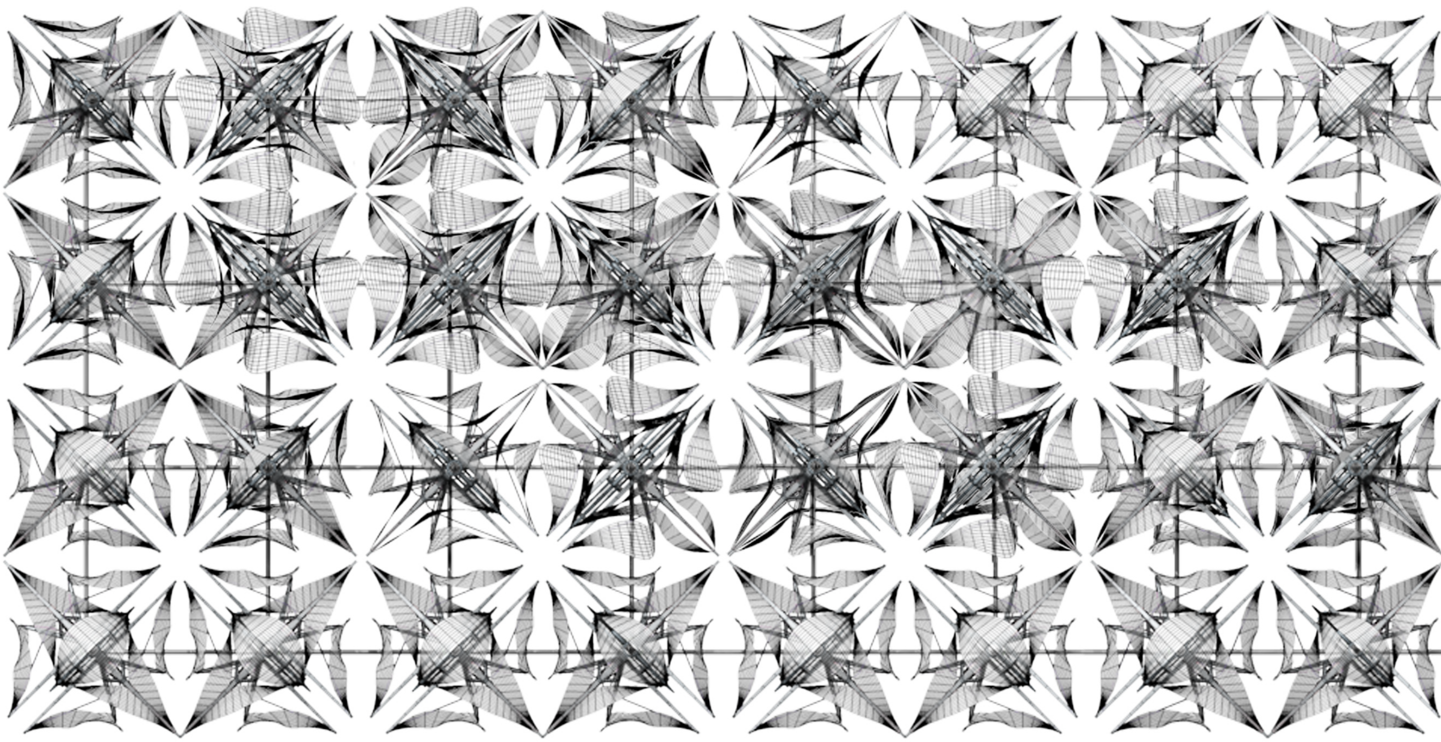
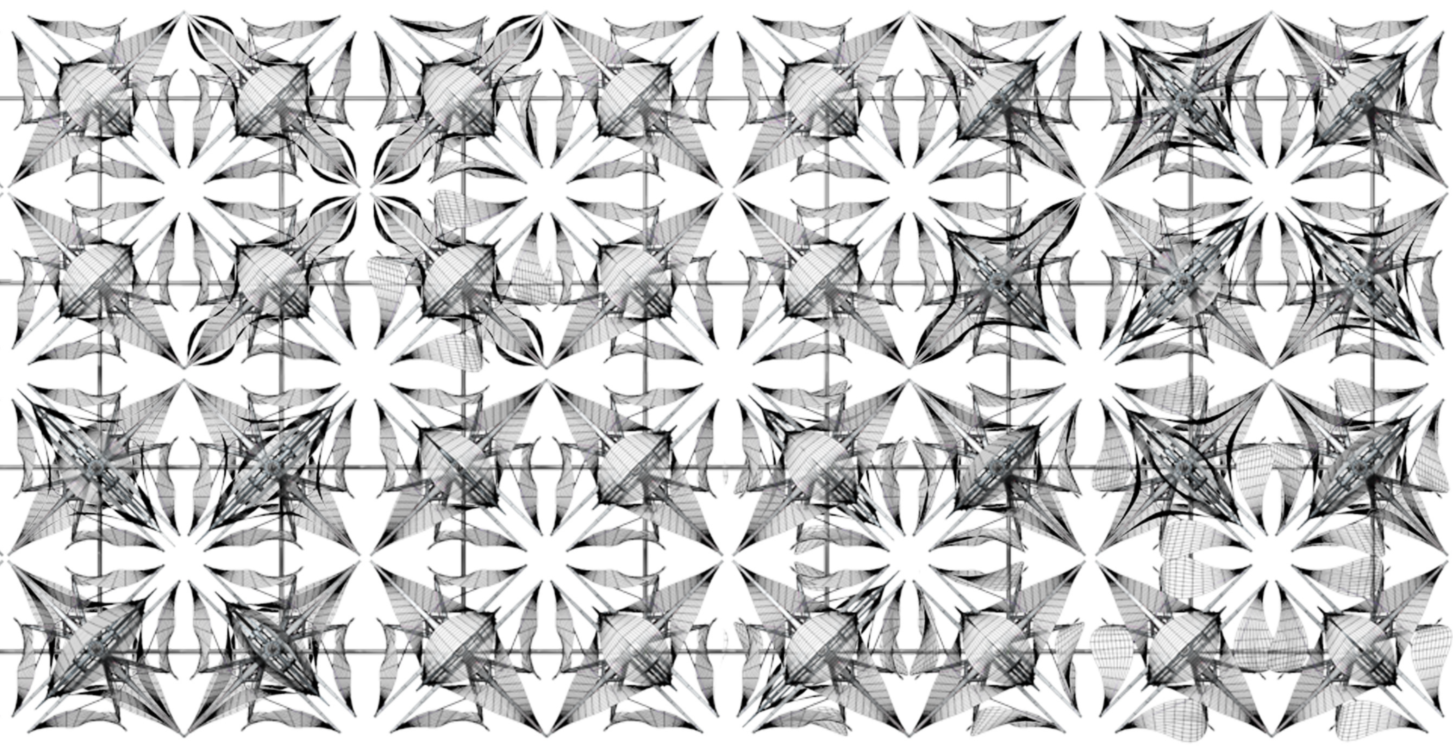
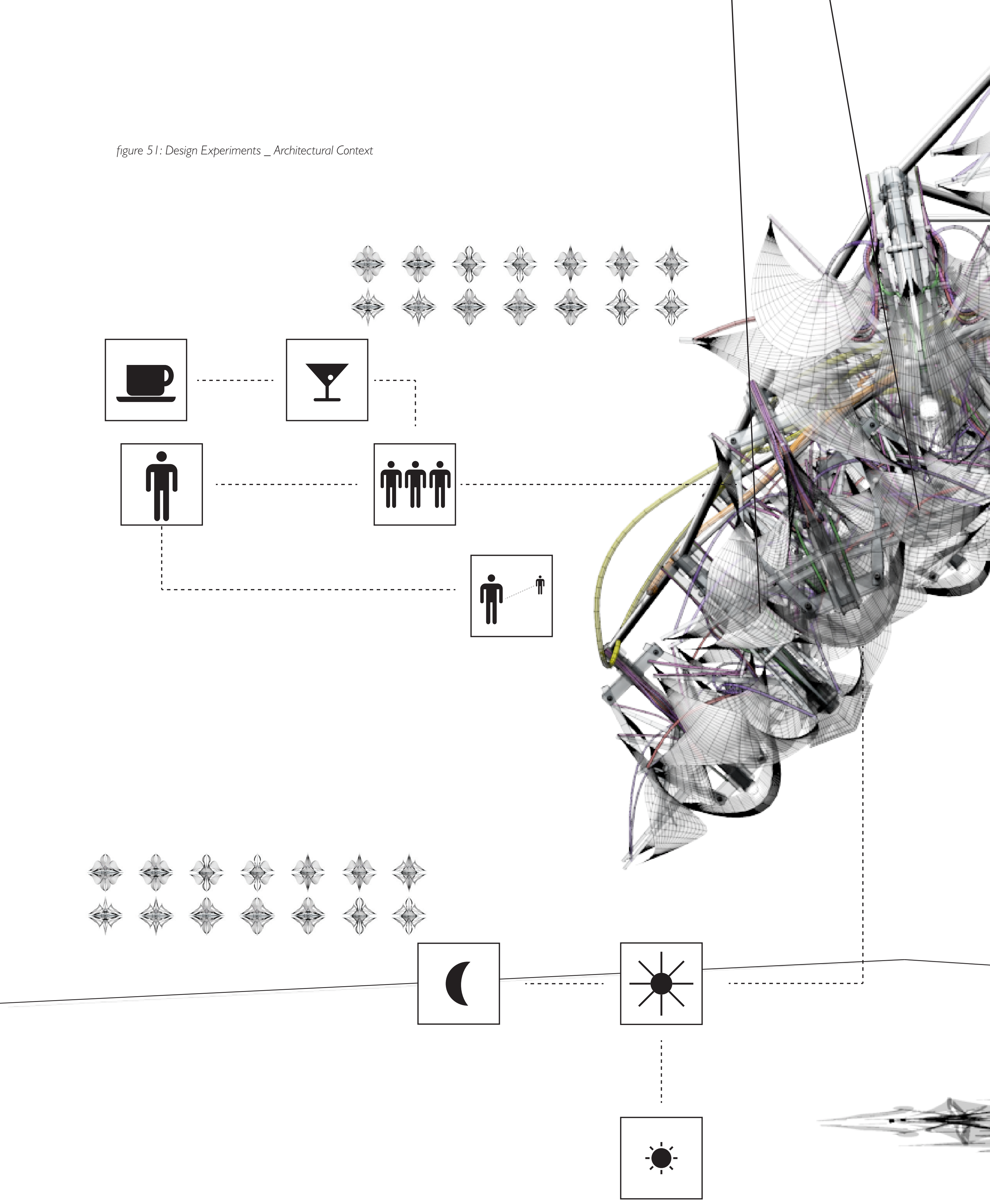


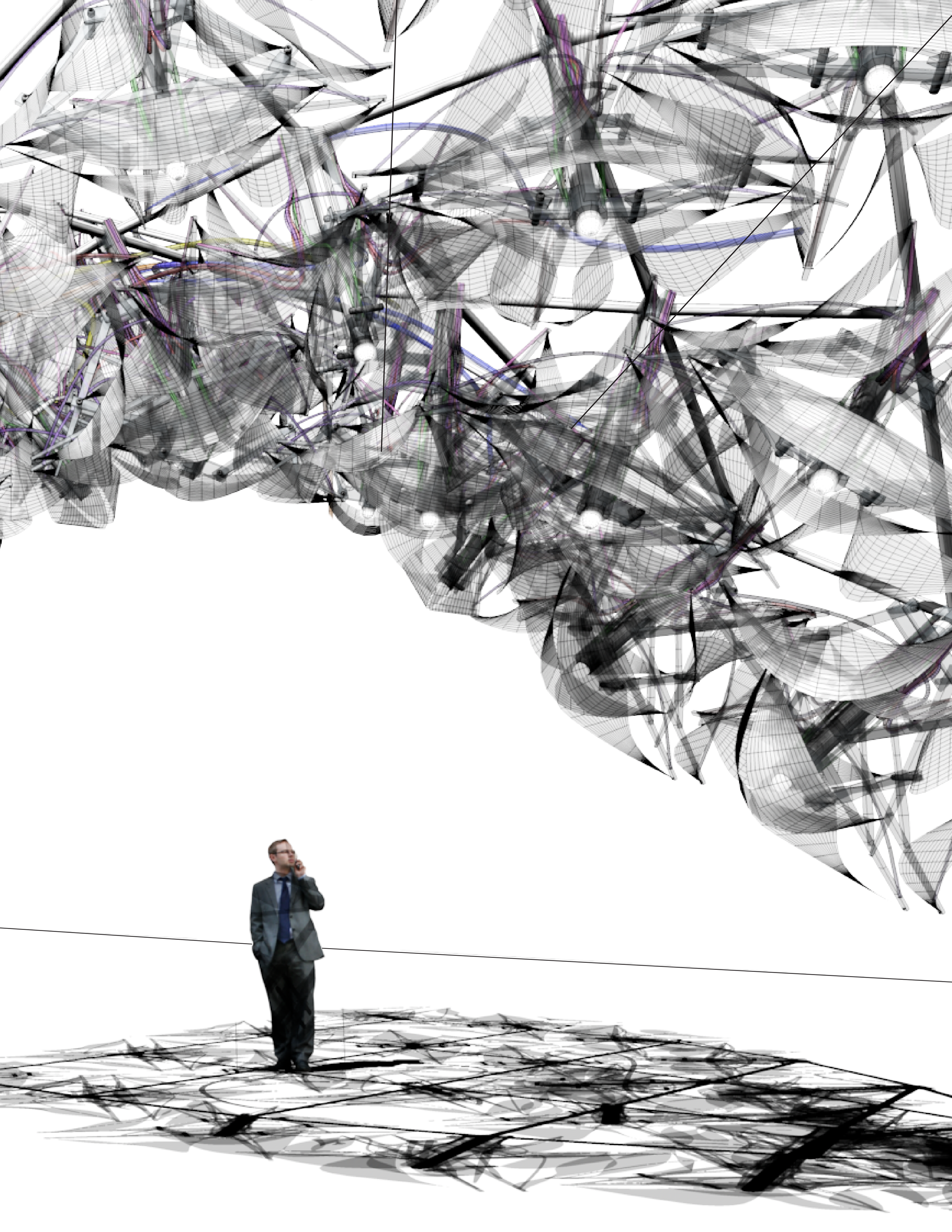
figure 50: Dynamic Array

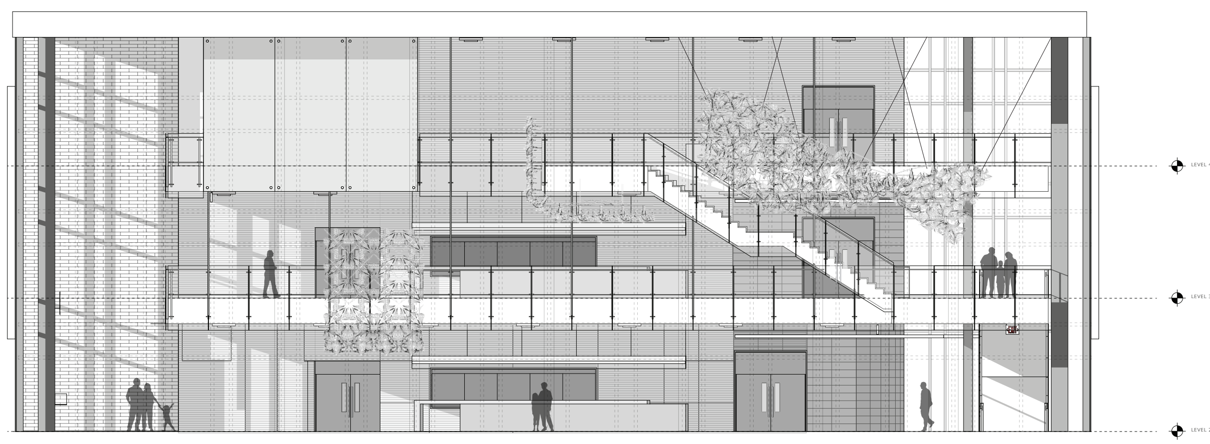


Through this superimposition of kinetic elements, an allotropic prototype (existing in multiple physical forms), is created to enable new strategies to engage with contextual forces inherent in the architectural medium. The Royal Conservatory of Toronto provides an interesting opportunity to engage with a confluence of wide-ranging contextual forces, including a variability of sound, light, users and program. *Allotropic Fields* populates an atrial space which serves primarily as an anti-chamber to the main performance space. It exists as a multi-level responsive architectural installation that interacts with variable lighting and acoustical conditions in addition to a plurality of social aggregation brought upon by both the formal and informal activities of the Royal Conservatory.

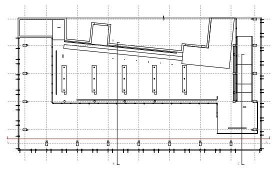
figure 51: Design Experiments _ Architectural Context





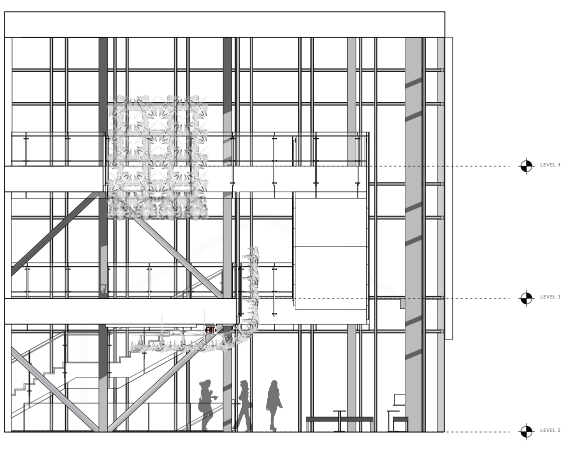


A _ LONGITUDINAL SECTION

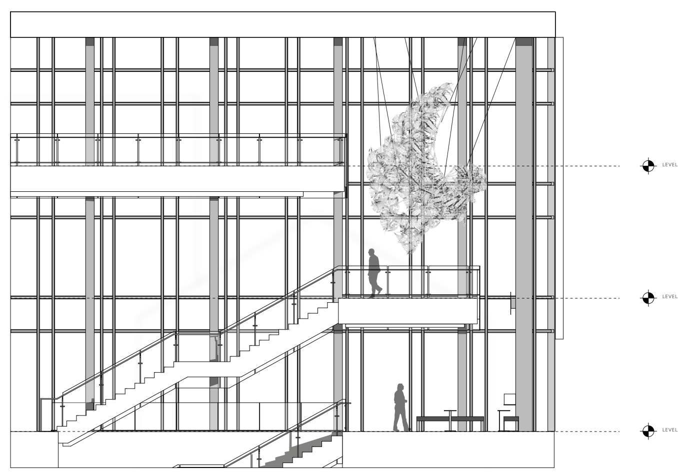


REFLECTED CEILING PLAN - LEVEL 2

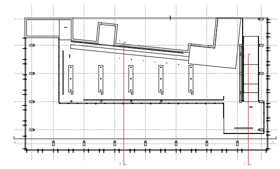
figure 52: Royal Conservatory of Music _ East Atrium _ Longitudinal Section



B _ CROSS SECTION



C _ CROSS SECTION



REFLECTED CEILING PLAN - LEVEL 2

figure 53 Royal Conservatory of Music _ East Atrium _ Cross Sections

figure 54: West Stair Approach

figure 55: Arrayed Assembly

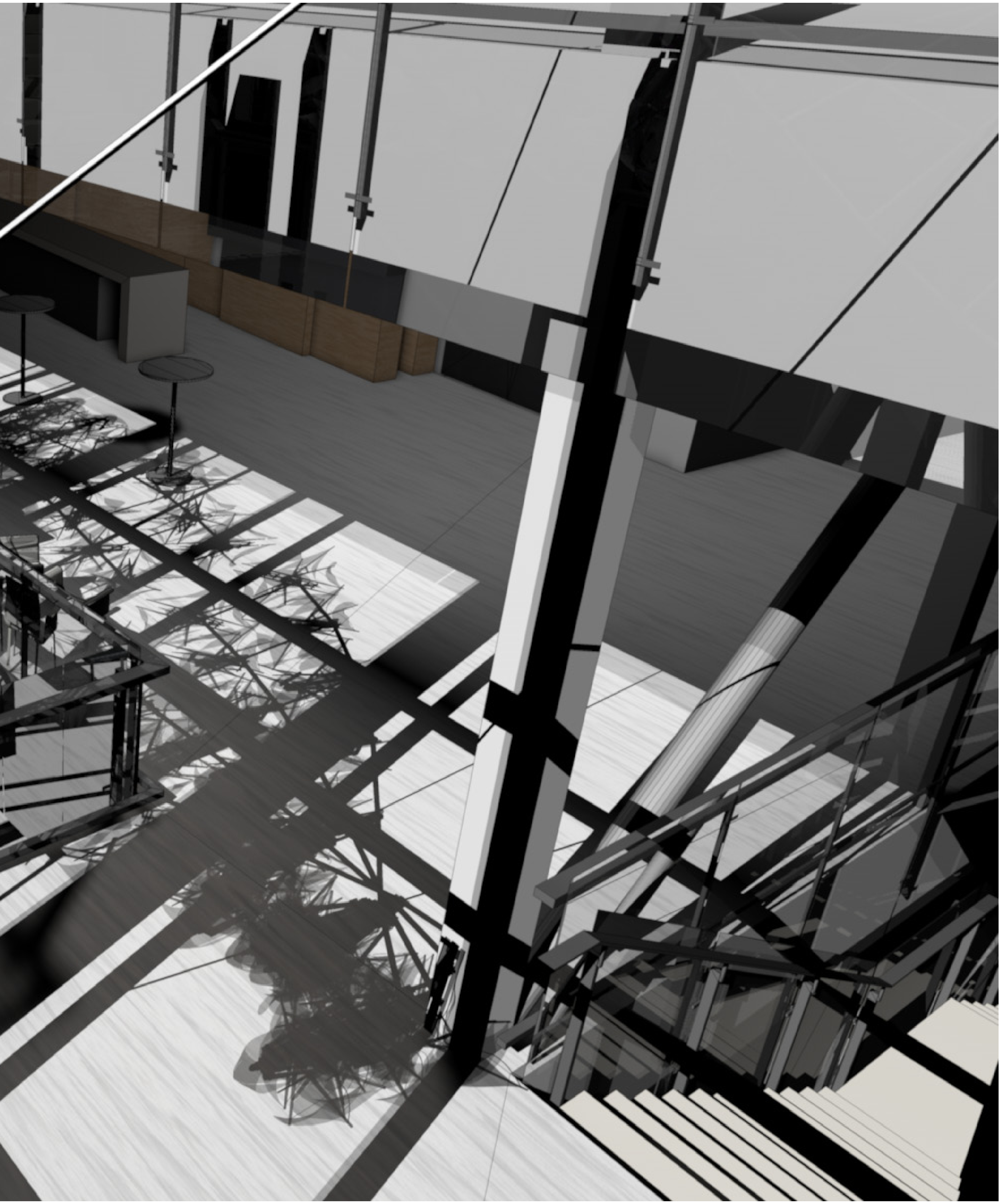


figure 56: Arrayed Assembly

figure 57: Allotropic Fields

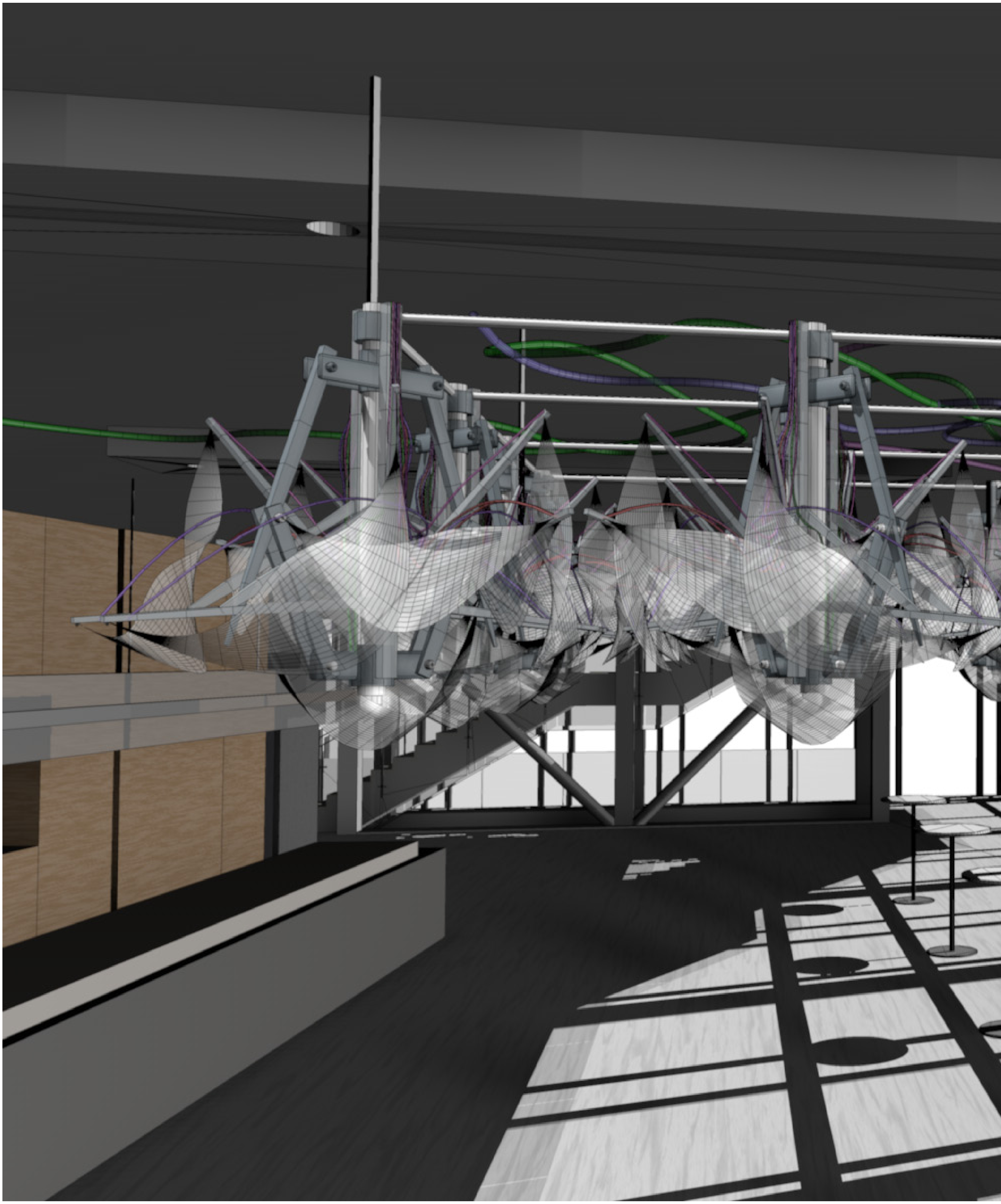
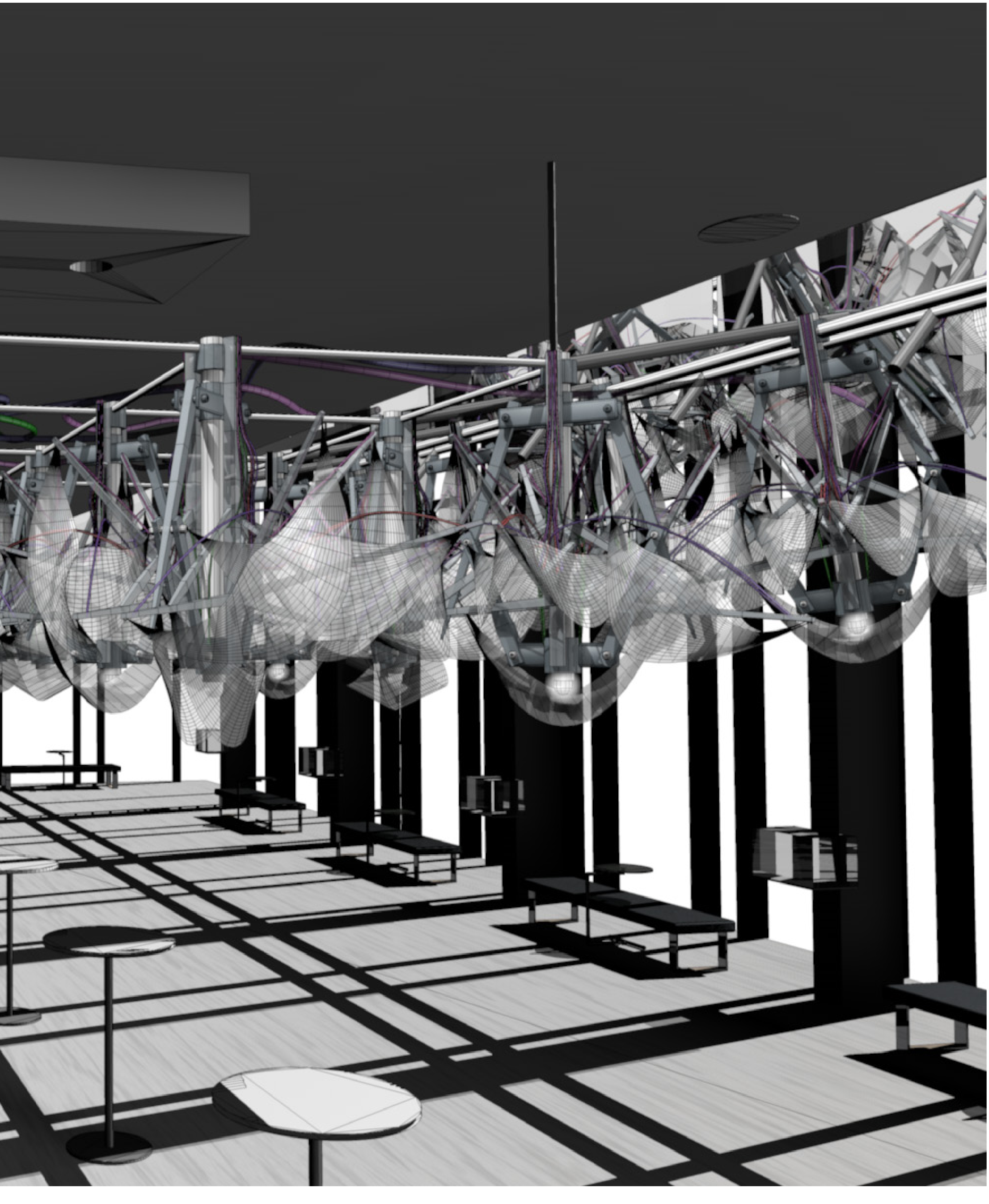


figure 58: Allotropic Fields



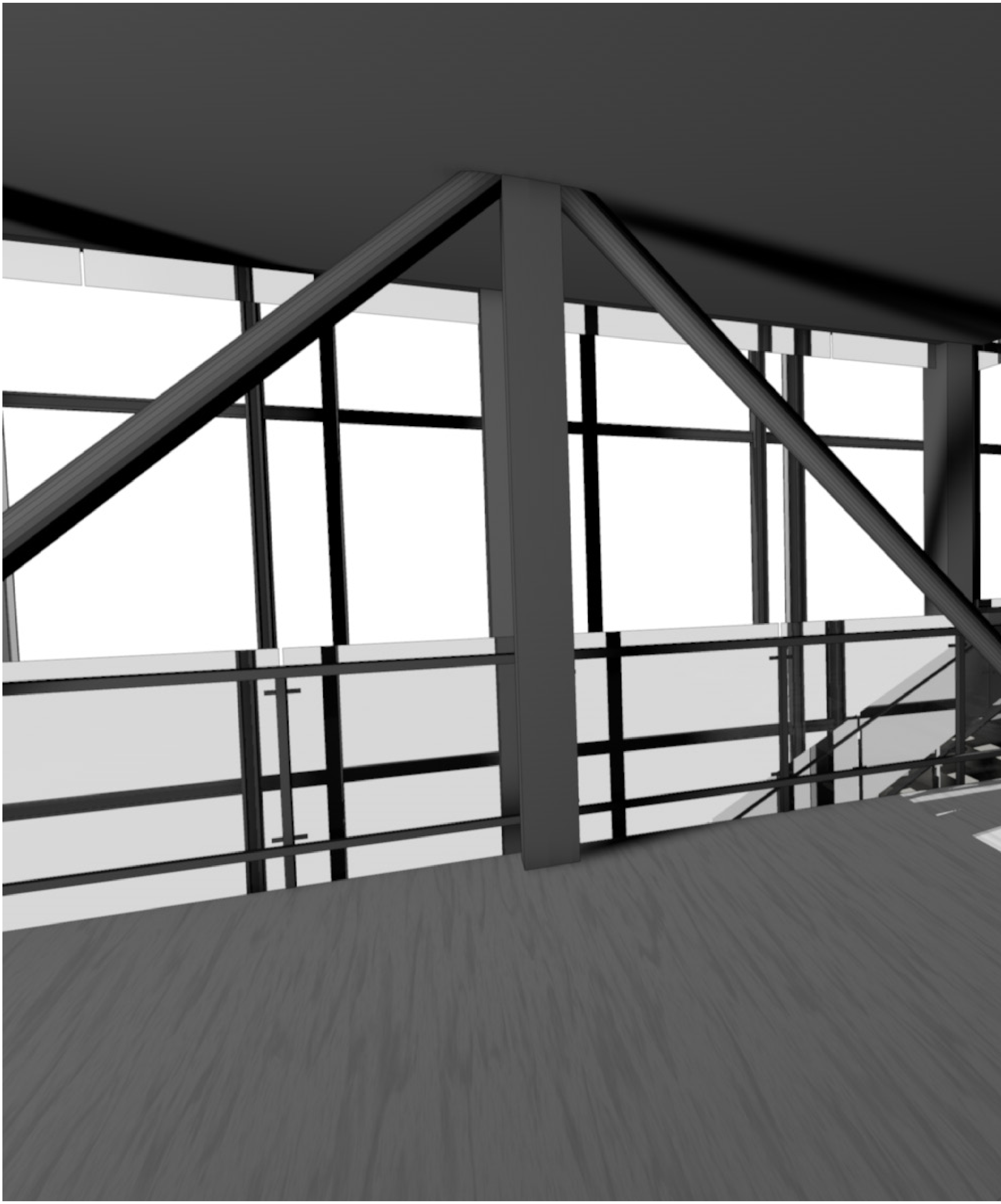
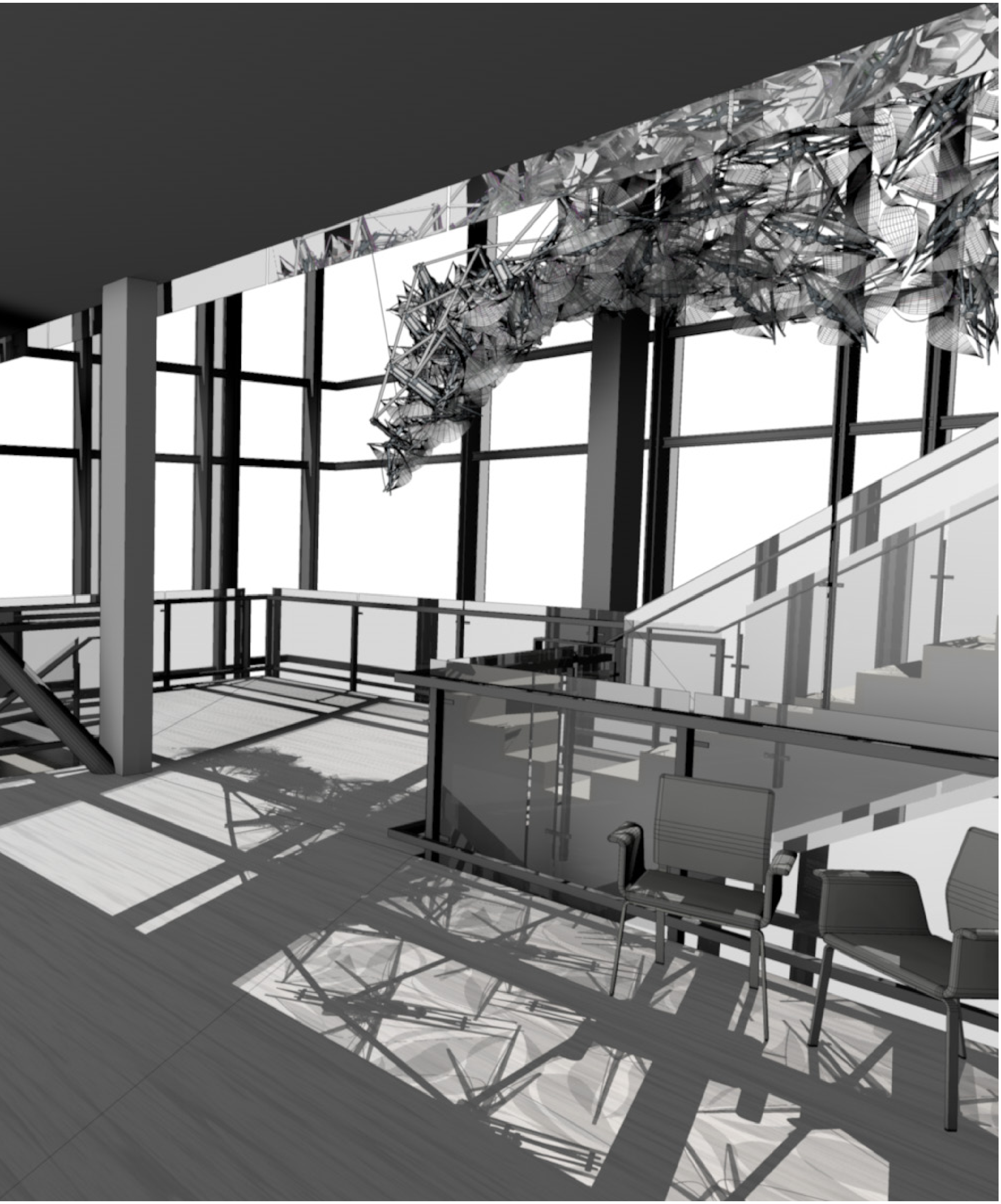


figure 59: Allotropic Fields



By analogy to biological systems, architecture has historically exhibited a limited capacity for adaptive behaviour. The evolutionary course of biological development has engendered an expansive spectrum of highly complex, ordered, dynamically adaptive mechanisms. Architecture, on the other hand has predominantly remained static where building materials and structural systems have historically been employed by virtue of their inherent abilities to withstand change and endure time. The recent development of robotics and ubiquitous computing though has engendered a potential for kinetic architecture to operate in conjunction with automated systems of sensory-actuating feedback. Through this inherent capacity to sense contextual conditions to, in turn react by virtue of real-time changes, adaptive architecture has found countenance in a contemporary society immersed in electro-nomadic spatial practices. By means of computational mediation, architecture is thus shifting from traditional constructs of stasis, towards those of dynamic engagement with the technologically influenced and changing patterns of human-building interaction.

Allotropic Fields extrapolates a future vision of this shifting architecture through the realization of kinetic installation that challenges the traditional assumptions about architecture as a passive arrangement. This thesis project was conceived as an interactive system constantly evaluating surroundings and reconfiguring itself through a layering of mechanical and material deformations ranging from independent fluctuations to multi-dimensional dynamic transformations. The emergent and sometimes incalculable behavior of the output device evoked progressive thinking about architecture, described by Mitchell (2003) as one ‘creating versatile, hospitable, accommodating spaces that simply attract occupation and can serve diverse purposed as required'. Allotropic Fields epitomizes this idea of architectural impact through complex kinetic responses in order to intelligently moderate human activity and the environment to in turn create an architecture able to extend our capabilities.

Resulting from the transposition of critical dimensions of complex biokinetics and animal locomotion, this thesis existed as a hybrid construct of physical explorations and theoretical interpretations and prognoses that evoke progressive thinking about adaptive architecture and its operative parallels with biological constructs. The most important achievement of this thesis was the materializing, albeit virtually, of an adaptive architectural assembly predicated on constructs of complex biokinetics and animal locomotion. This procedure triggered new ways of thinking of architecture as a fusion of scientific and artistic disciplines. The dynamic properties of this multidisciplinary thinking transcended the physical and theoretical boundaries that deprive conventional architecture to fulfill its role and function in society by responding adaptively to the rapidly emerging changes in our culture and environment.

Appendix A_ Biological Adaptation

In biology, existence and reproduction maintained through adaptability to change are the supreme values of life. Evolutionary history is filled with overspecialized species that became extinct because they lost their capacity for further adaptation. Adaptation is clearly the key to long-range biological survival. However, to narrow the field even further (again for later architectural relevance) a time-scale factor of adaptation will be imposed. Adaptation or evolution through the successive mega birth-death cycles of a particular species will be excluded from these discussions. Although such long-scale overviews are valid and of importance in both nature and architecture, only adaptive systems relevant within a single life span (or at most several) are realistically appropriate to the concept of kinetic architecture being expounded. The following section will survey the basic types of adaptive, actuating responses in organisms (Zuk & Clarke, 1973).

Component Movement in Plants

In plants, adaptive movement of components within the overall entity is called tropisms. A variety of tropisms exist such as phototropism (response to light stimulus) heliotropism (response to sunlight resulting in twisting), geotropism (response to gravity forces), hydrotropism (response to the presence of water) and haptotropism (response to touching). Haptotropism is particularly interesting as it is almost an animate quality. Three examples of this movement are the waving and turning action of tendrils of the pumpkin plant searching for a support to grip; the sudden nastic closing of the trap of the Venus's flytrap when certain hair-like sensors are touched; and the detugorization, or wilting, of the leaf stalk of the *Mimosa Pudica* plant when pressed (Gefen, 2011).

The mechanisms of such adaptive motions are ingeniously simple mechanically, yet complex chemically. The tropisms of all the examples cited, except for the Venus flytrap and the *Mimosa*, are due to localize accelerated cell growth. To move in a certain direction, the plant merely adds more cells in a given location. For example, for a root to turn a corner to find more water, the root grows more cells on one side of the root over a small distance, and the expansion of this side causes the root to bend at that position. The full explanation of how the plant does this is still under study, but the regulation of this growth is believed to be due to a special plant hormone, or auxin, in an as yet imperfectly understood manner (Gefen, 2011).

Some of these growth movements can be moderately rapid, observable by the unaided eye over the course of several minutes. Rapid movements as in the cases of the *Venus* flytrap and the mimosa stalk require a different activating mechanism. This mechanism is fluid osmotic pressure. For example, in the haptotropism movement of the *Mimosa* leaf stalk, external physical contact with this portion causes water to escape from certain pressurized thin-walled cells into intercellular void spaces. The stalk, then relived of its pressure, wilts, much as a balloon losing its air pressure deflates. Structural rigidizing and control by means of pneumatic and hydraulic pressure (Gefen, 2011).

Component movement in creatures

The controlled movements of elements of insects, fish, animals, and humans are generally more obvious. Movements in such living creatures are primarily achieved by muscular action. In this case of limb-like members, essentially straight muscle fibers are connected between two adjacent rigid bone members, with the bones being loosely connected in a ball and socket joint. Nerve controlled contraction of the muscle fibers then causes a kinematic movement of the bone structure to be induced in a variety of directions. This simple principle of leverages is capable of producing very rapid and strong forces.

Muscles are capable of only contraction. Therefore, for a member to return to this initial or reverse position, some opposite force must be exerted. Generally this opposite force is supplied by an opposite set of muscle fibers, called extensors, but in some simpler movements (as in insect wing flight kinetics) the reversal is by elastic flexure. In the insect, the wing is organically attached to the stiff thorax of the body and the single set of flight muscles pull only one way. The wing returns by elastic spring back, when pulled again by the one-way muscles to create repeated movements.

Another form of muscular action is that of peristaltic contraction. In this form the muscles are essentially annular, usually arranged in parallel groups like rings around a tube. It is by this mechanism that cylindrically shaped components can be made to dilate radially or even to extend longitudinally. Peristaltic muscles may be found in such places as the body wall of earthworms and snakes, intestines, and oviducts. The ovoid shape of a chicken's egg is, in fact, form by the varied pressures exerted on the formative eggshell and its fluid interior as it passed through the peristaltic oviduct. The great spatial change required in the body of a snake or fish when it swallows a creature larger than itself is also made possible by the adaptive mechanism of such peristaltic muscles. Peristaltic movements of this form have an important application in kinetically controlled pneumatic structures (Klette, 2008).

Free Body Movement

Natural movements thus far discussed related primarily to local or component motion. Another category of movements deals with free body or total entity movements, in which the whole system moves in relation to its environment. In most cases, this movement also is for adapting to a need, as for the active need of acquiring food energy or the passive need of environmental protection. In architecture the need for total mobility is for other adaptive needs of the user, such as growth and change. However, many of the motive aspect of nature provide a useful insight.

Locomotion in nature may be either passive or initiative. The category of passive locomotion includes movement by fluid stream or air transport, physical attachment to another moving body, and gravity, all conditions in which the object moved does nothing itself to produce motion. An example of each of these in respective order is: drifting of jellyfish by water currents, the rolling of tumble weeds by wind action, the transport of certain plant seeds by barb attachment to passing animals, and the vertical motion of falling seeds and fruits. Although hundreds of examples may be cited, only these will be mentioned since parasitic locomotion is of lesser importance to kinetic architecture than is initiative locomotion. Initiative locomotion is defined as locomotion through an environment of any medium (water, air soil, wood, etc.) by virtue of the entity's own controlled kinesthetic and kinetic abilities.

There are three basic biological devices for initiative locomotion, namely, ciliary, muscular, and hydraulic. Cilia or flagella are thin hair-like growths of protoplasm outcropping from the surface, formed in closely spaced groups. For locomotion, they wave rhythmically, visually like a wheat field undulating in the wind. As such ciliary energy output is small; this motive device is effective on only very small fluid borne creatures. Muscular activation, in contrast, is effective in far more situations, providing propulsion in almost any environmental media, for large creatures as well as small, for rapid motion as well as slow. The three most common environments are air, water, and earth, along with their interfaces. Other less common environments include the vacuum of outer space (containing spores), the interior of other creatures (containing viruses), and the interior of plants (containing endo-parasitic insects and worms). As these latter environments have little relevance to architecture, they will not be dwelt upon (Klette, 2008).

The best reference to date on locomotion through the environments of water and air by swimming and flying respectively is found in the book *Structure-Form-Movement* by Heinrich Hertel (1966). To summarize, the fundamental principle of motion in a continuum such as air and water is predicated on creating, by dynamic action, a differential pressure on the subject in the direction of motion. The ways in which this is done in nature, however, are vast in number. The most common device is that of a broad surface (such as air or water) through muscular action. The resistance offered by the continuum thus acts as the propulsive force. As our early wing-flapping aviation pioneers discovered, a fixed surface merely oscillating back and forth does not work, as the resistance in both directions of oscillation is the same. The end force and movement are thus both zero. Rather, the surface must adapt to different configurations during a given flap cycle, as well as during various maneuvers, such as ascending, descending, accelerating, decelerating, cruising, and turning. The same principles are those upon which aircraft engineers determine their lift and drag requirements. At high speed or supersonic flight, the wings are folded back; at low speed landing, the wings are fully extended (Hertel, 1966).

A further analogy may be drawn between the rotating propeller blades in an air or undersea vehicle and the cyclical movement of nature's flap, both creating propulsion by pressing against the resistance of the ambient medium. For creatures navigating through interfaces, such as earth and air or water and air, muscle action is directed in another way. On these surfaces, surface pressure against the denser medium provides the motive force. The most common examples of interface creatures are those of land-based insect and animals, including man, although examples of water surface-based creatures such as the *Gerris* and *Collumbola* water bugs may also be mentioned. Insects living inside relatively dense substances, such as soils, wood, or plants, may also be considered as operating on an interface of the solid and the void, employing basically the same propulsion processes as for land-air interfaces. Novel boring methods, however, may be used; for example, earthworms ingest soil particles in the boring end and expel it at the tail end (Hertel, 1966).

Appendix B _ Actuation Materials

As technology advances, materials, such as metals, that are typically utilized in the development of mechanical systems, including actuation systems, are progressively being substituted by materials that respond to an external stimulus with similar mechanical characteristics as their predecessors. Two classes of these actuation materials include shape memory alloys and electroactive polymers.

Shape memory alloys (SMAs) are metals that have the ability to undergo a solid state phase change between the phases of martensite and austenite. At low temperatures, the deformable martensite is of the same cubic structure as the stronger austenite phase. At high temperatures, deformation of martensite occurs, which results in a deformation of the austenite phase. When the alloy is cooled to a certain temperature, it is entirely composed of martensite, and can be deformed into any shape. This is known as the shape-memory effect, and this process can be repeated many times over. The force generated when the material returns to its original shape can be used for actuation purposes.

However electroactive polymers have shown superior performance characteristics over shape memory alloys. Shape memory alloys have been shown to have similar strain characteristics, and demonstrate elastic behavior. However, the power requirements are similar to those of electroactive ceramics, and have a very slow response speed. In addition, the convenience found in the use of electric field activation of electroactive ceramics and polymers is lost with shape memory alloys, which require temperature changes to provide their mechanical functions. As such, for applications that require a large force to be developed at a high speed, electroactive polymers have been deemed to be one of the best set of smart materials available (Lin, 2008).

Electroactive Polymers

Electroactive polymers are novel materials that are increasingly being taken advantage of for their large deformation ability and low mass. These materials have been found to transform electrical energy into mechanical energy through the production of large strains. As polymers, these materials can be fabricated into numerous configurations by a variety of techniques, and are mass producible. They are also relatively inexpensive, as they do not require magnetic charging, which is unlike their ceramic counterparts. Electroactive polymers are also physically tough so as to not fracture into two when placed under an applied load. One drawback in the use of electroactive polymers is their relative inefficiency, and thus, it has been determined that while electroactive polymers are superior to other active materials for actuation, they are not optimal (with the exception of acrylic dielectric elastomers) for use as electromechanical generators (Xue, 1998).

Electroactive polymers have been shown to have superior actuation characteristics than shape memory alloys. Strains of as low as 0.1 percent for piezoelectric polymers and as high as 380 percent for dielectric elastomers have been reported. Stresses ranging between 0.3 MPa and 450 MPa have been reported; however, these stresses have both been reported with relatively slow response times. Dielectric elastomers have been shown to have the best electromechanical efficiency; however, the efficiencies for a number of other electroactive polymers have not been reported. The one main drawback with many electroactive polymers is the requirement for high activation voltages, which typically is on the order of kilovolts. Electroactive polymers can be subdivided into two categories based on their activation mechanism and their actuation characteristics - ionic and electronic electroactive polymers (Xue, 1998).

Ionic EAP

Ionic electroactive polymers are activated through a transport of ions or molecules that is developed by an applied electric field. This diffusion of particles results in an internal stress that, in turn, results in strains in one or more geometric orientations, including volume expansion, volume contraction, and bending. Presently, there are a number of different configurations of ionic electroactive polymers; however, each consists of two electrodes and an electrolyte. Examples of ionic electroactive polymers include conductive polymers, ionic polymer gels, ionic polymer-metal composites, carbon nanotubes, and electro-rheological fluid (Xue, 1998).

There are a number of advantages in using ionic electroactive polymers over their electronic counterparts. First, the activation voltages required for actuation are much lower than that of electronic electroactive polymers, on the order of one to two volts. They are also good for bending actuation, and can be actuated bi-directionally based solely on the polarity of the applied voltage.

However, ionic electroactive polymers need to be kept in a wet state, and it has been found to be difficult to maintain a displacement under a direct current voltage. This latter disadvantage, however, is not applicable to conductive polymers and carbon nanotubes. Ionic electroactive polymers are also slower and develop lower actuation forces than their electronic counterparts.

They have also been found to be difficult to produce in a consistent manner, making them difficult for mass production. Finally, these materials undergo electrolysis separation at voltages greater than 1.23 volts (Xue, 1998).

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