Kinetic Wall
an exploration into dynamic structure

by
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| Thanks                                      | Kevin Fellingham, Paul Keel, Marios Christodoulides, Anahid Tokes, “Lucky” @ Joe Factor Sales, LA, Tako |
abstract

The existence and survival of an organism in any given environment is the ability to adapt and change to that environment. Living entities are far more adaptable to a changing environment than anything produced by human design. Buildings exist at a very low level of sophistication when compared to any living organism. Living organisms are able to adapt to a changing environment with the aid of many specialized systems working in conjunction; circulatory system, nervous system, structure system and means of motion.

For a building to exhibit this kind of sophistication, the integration and design of such active systems must be investigated. With new advances in the engineering of smart materials, computational control mechanisms, and robotics, this is potentially feasible.

My research focuses on the development of one part of such a system; a computer controlled kinetic surface structure or kinetic wall. This system can be adapted to work as an sculptural internal space divider, a façade for an existing building, or a large scale dynamic roof system. The current prototype precedes the development of a fully integrated sensory feedback system, which when added could potentially be a first step towards a truly active building.
Contents

Abstract 5

Why do organisms move? 9

Concepts of Space 10
  relativity 12
  space, time, architecture 14

Boundaries of form 14
  Serra's Torqued Ellipses 15

Natural Form and the Human Hand 16
  Bone Structure 16
  Interossdous and Lumbrical Muscles 17
  fibrous flexor sheaths and tendons 17
  assesment 18

Surface explorarions 20
  Paper folding 20
  folds and resolution 21
  Scale-less form 22
  Recursive surfaceness 22
  Triangles and resolution 23
  Surface extension in 3d 23
  Curved shells & Hyperbolic Paraboloids 24
  Crossing patterns & Structure 26

Kinetic Wall 28
  Basic Structure 28
  One bay 29
  Two bay 29
  Four bay 29
  movement 29
  control 30
  Computational integration & Control 32
  Potential uses 33

Bibliography 36
Why do living organisms move?

Living organisms move to survive. A universe in constant movement forces bodies, inert and live into action. A planetary body's mass works for and against other bodies in space causing planets to rotate, oceans, waves, weather, and man to move.

Space and form as twentieth century architectural ideas can be described as existing in three overlapping realms; perception, mimesis, and physics. One could argue that of them perception and mimesis are derivatives of physics but share a strange balance of power in the way we discern the formal characteristics of space.

To describe a space or its essence we often begin by laying out its physical characteristics, color, shape, height, size, all definable physically determinate characteristics. To describe the experience of the space beyond a physical based description, we often talk of analogous feelings or representations that come to mind. These descriptions are often analogies or shared perceptions that we graft on to the one we wish to describe. Together they form a total perception of a space and form.

Only in the last century has human perception of motion and movement begun to influence ideas about form in architecture. These ideas have undergone a transformation replacing metaphysical views of the world to one of science based perceptual evidence.

It is this concept of space combined with a physical description that begins to order perception of space. Perception of space is now inseparable and imperceptible without movement.
Concepts of Space

Pre-renaissance concepts of the universe were in equal alignment to architectural ideas of space. Often towns and buildings were conceived as the unequivocal center of the known universe. For example Rome and Vatican City as planned by pope sixtus. Now concepts of space in architecture have stayed at a relatively low level of Now the universe can only be understood in the discrete language of mathematics and architecture and building are understood with pre-modern physics.

The concept of space and its relationship to that of ‘form’ have drastically changed since the renaissance and modern cosmology began to reinterpret the conditions of space and its nature. Space has been one of many concepts that had its absolute metaphysical origin reinterpreted into the realm of secular and science based interpretations. If we are to understand dynamic form, it is worth briefly going over this transformation of the concept of space and its relation to movement.

Henri Lefebvre in his book The Production of Space charts the progression of space as a concept first described by Leibniz as ‘infinite’, ‘indiscernible’ and attributed to God and then transformed post-enlightenment into an idea purely of measure and science. The experience of space and spatiality for Lefebvre is not one of either realm; empiro-scientific or divine providence. It is one of dual modalities and only truly experienced through spatial ‘occupation’. Lefebvre explains this through perceptual experience:

The observer stands perplexed before the beauty of a seashell, a village or a cathedral, even though what confronts him consists perhaps merely in the material modalities of an active ‘occupation’ - specifically, the occupation of space... The poetry of shells - their metaphorical role - has nothing to do with some mysterious force, but corresponds merely to the way in which energy, under specific conditions (on a specific scale, in a specific material environment, etc.), is deployed; the relationship between nature and space is immediate in the sense that is does not depend on the mediation of an external force, whether natural or divine. The law of space resides within itself, and cannot be resolved into a deceptively clear inside-versus-outside relationship, which is merely a representation of space.
All this seems very obvious when a space of neutral void or emptiness is taken over it suddenly gains presence by a form and its relation to the void. As in the case of a cup and the water it fills. But Lefebre brings up a more important point concerning its existential nature. What are the laws of space in relation to this? If they are defined by the laws of form and form is defined by the laws of physics? This is a quite trivial line of thought that ends with physics and Lefebre rejects it. If the nature of space is in its supernatural observation or occupied nature what can we use to define its boundaries?

If the sensation of space is indeed occupation and not simply one of external versus internal relationships R. Buckminster Fuller takes this view one step further asserting that not only does the idea of inside and outside not matter, space has relative properties only definable as high-frequency events that all exist within relative spheres locality.

"There is no universal space or static space in the Universe. The word space is conceptually meaningless except in reference to intervals between high-frequency events momentarily "constellar" in specific local systems. There is no shape of the Universe. There is only omni-directional, nonconceptual, "out" and the specifically directioned, conceptual "in" We have relationships but not static relationships."

Again we get another similar interpretation concerning relative conditions in the terminology of science and this time directly pointing towards relativity theory. Einstein's relativity Theory was a building on built on Newton's view and Riemann's ideas of elemental geometry and form.
Relativity

The important part of relativity theory is that it points towards one hallmark and central difference from the earlier Newtonian theories of space classical mechanics: motion.

Motion in Einstein's Theory of Relativity is inseparable from time, and space. Discrete perception of any one aspect of space or a body in space can only be taken as a whole and as a piece of a greater total event that is in itself relative to other entities in space. This holistic view of space and the universe was drastically different from a Newton's universe of discrete elements.

Newton separated different events within space, and aspects of it: position, mass, speed, and time were separately definable aspects. For example if you were to examine a body in space you could characterize it as having a given location in space; x, y, and z coordinate point values in Euclidean space, a mass, a velocity, and a specific time when the object existed in space. (fig.1)

If you were to examine objects in this space each object would have its own separate characteristics. To describe one object we can visualize it in two-dimensional space having two coordinates and time. (fig.2)

For an object in Euclidean three-dimensional space we can rewrite the equation with each coordinate squared plus time. (fig.3)

We have ordinate pairs in three coordinates and time. Notice that 'time' is one dimensional since it is imaginary, linear and unknown.

In relativistic space-time the equation is rewritten with time and the speed of light as a constant. (fig.4)

With this we have coordinate position of the object in space and its relation to spacetime.
The reason for the minus symbol is the sticking point here. With any given object in relativistic models of space time, time is always a function of the speed of light. (fig.5) Since time is itself an imaginary concept it has been given an imaginary number, hence the minus. (fig.6)

\[ I = (-1)c^2t^2 \]

\[ I \] is the imaginary constant, \( c \) as the speed of light and \( t \) as time.

Time is also relative depending on where you are in space.

To solve for a given length or triangulate the location of an object we can rewrite the equation solving for length. (fig.7)

\[ l = \sqrt{x^2 + y^2 + z^2 - (ct)^2} \]

Transposing the equation and solving for time we can see time as having an inverse and direct relationship to the speed of light. (fig.8)

\[ t = \frac{\sqrt{l^2 - (x^2 + y^2 + z^2)}}{c} \]

So for relativistic models of space we can look at time as a function of the speed of light and its position in space. Motion time and space itself become inseparable for all events occurring in space.
Sigfried Gideon:  
Space, Time, Architecture

Motion and modern conceptions of architecture run through Sigfried Gideon's interpretation of modern architecture in *Space, Time, Architecture*. Gideon saw motion and time as aspects of architecture and space that were fused into the zeitgeist of the modern epoch and its form-makers. If form and motion were linked to space here was an architectural theorist and historian who saw that not only was it the underlying motivation, it was the common link.

Gideon viewed the forms in contemporary architecture as the manifestation of the freedom and motion of a free society.

**Structural Engineering**

Contemporary structural engineering advances were moving away from simplified notions of form and the methods of engineering those forms:

Twentieth-century structural engineering is moving along a different path. The tendency to activate every part of a structural system instead of concentrating the flow of forces into single lines or channels continues to grow. Such systems can expand with full liberty in all directions. This results in certain difficulties. The forces cannot be easily controlled: often they evade precise calculation. Only tests by means of models and mock-ups can help. Construction merges with the irrational and the sculptural.

**Boundaries of form**

He goes on to speak of form and the past limits of it:

Forms are not bounded by their physical limits. Forms emanate and model space. Today we are again becoming aware that shapes, surfaces, and planes do not merely model interior space. They operate just as strongly, far beyond the confines of their measured dimensions, as constituent elements of volumes standing freely in the open.

Sculpture and architecture were seen to fuse into one.
Torqued ellipses

If space is indeed ‘indiscernible’ by itself and existing only by virtue of its occupation one cannot find a better example of this occupation than in Richard Serra’s recent project “Torqued ellipses”. Serra’s installation consists of a series of three ellipsoidal arcs of two inch thick Cor-ten steel at a height of twelve feet and average ellipse of twenty-nine feet by twenty feet. The third series of torqued ellipses is an offset grouping of concentric ellipsoidal arcs that begins to describe a kind of architectural monument.

The torqued ellipses work by their pure existence in the space of the open gallery. They are at once recognizable as arcs or tubular sections and then seen in their apparently precarious state of cantilever or overhang. Because of the scale of the pieces the overhang or twist of two ellipses on a central axis one gets the impression that they are about to collapse.

The monumental presence of such simple but indiscernible objects that begin to occupy and describe the empty space of the gallery begins give the viewer a sense of his own scale in relation to these large objects. This sense of scale is clearly visible as the viewer walks around and inside the ellipses. Serra has aptly titled the piece Torqued Ellipses, giving allusion to the process of manufacturing or twisting the sheets of heavy steel as well as motion or movement that the word torque literally describes.
The Human Hand

The human hand is a highly specialized instrument. As a mix of biology and engineering, it far surpasses any attempt by man to mechanically reproduce it. The human hand can be viewed as the model of a perfect robotic appendage. In the hand we have a wide variety of specialized muscles, tendons and ligaments that is combined with a set of sensitive nerves and sensory receptors. This allows the hand to at once sense and manipulate objects and assume a number of different positions required to grasp, handle manipulate as well as create other objects.

This analysis categorizes it into four categories: muscle and tendon systems, bone structure, skin structure and nerve and sensory systems. I specifically avoid an analysis of the thumb and the muscles over the metacarpals because I am looking at only the motor coordination and structure of the four fingers for any clues that may help in the design of a similar repetitive system. Nevertheless the opposable thumb and the orchestrated combination of all systems working in harmony is what produces the almost transparent function and usage we experience everyday.

Bone Structure

The bone structure of the hand as documented in anatomical texts looks at the structures of the hand as groupings of ascending bones that make up the fingers. The main bones as extending from the base of the smaller bones in the hand are called metacarpals. Each metacarpal bone supports a set of successively smaller bones called phalanges. The three phalanges are termed proximal, middle, and distal.

Bone structures in the hand are hierarchical and follow a descending ordered progression from the two bones that support the wrist. The bone structures of the hand each incorporate special connections that allow each successive bone to support the attachment of muscles, joints, and tendons, as well as the next bone it supports. In this way the bones...
of the hand can be looked at as only one part of a larger system that cannot work independently of the others.

**Interosseous and Lumbrical Muscles**

Often referred to as the “deep hand muscles” the lumbricals and interosseoi are the main muscles that control finger rotation around the base joint of the finger or the top of each metacarpal. There are four lumbrical muscles two originate from the lateral side of the flexor digitorum profundus of the index finger and the middle finger. The other two originate from the adjacent side of the flexor digitorum profundus of the other two fingers (ring-finger and pinky).

It is because they pass from the anterior or front of the palm to the dorsal or side of the digits, they can flex the fingers at the top of each metacarpal bone.

**Fibrous flexor sheaths and tendons**

On the lower or anterior side of the hand there are five long flexor tendons that are enclosed in smooth tube like structures called synovial sheaths. The synovial sheath is simply a smooth fibrous sheath that is incorporated into various tendons in the hand. Here the sheaths are anchored on each phalange or finger bone. This anchoring by the fibrous flexor sheaths completely covers the lower side of each phalange. This creates a cylindrical space in which the long tendons can run through.

There are two tendons running through each fibrous flexor sheath on the anterior side of each finger. These tendons are called the flexor digitorum profundus and the flexor digitorum superficialis.

This system of tendons effectively acts like a series of pulleys. Together with the lumbricals and interosseoi, each tendon can control a separate finger without interfering with the control or movement of any of the other fingers.
Assessment

Building structures and other man-made structures are often conceived as stand alone systems. In the hand we have a totalized system of structure, muscle, tendons, and joints all working in conjunction to produce a unique indispensible part of the body. In a building or manmade system this integration is often piecemeal or by component parts that are designed for general wide-spread use. The hand is unique because the combination of the different systems is highly integrated and specialized. Can this kind of integration and flexibility be achieved in a man-made object?
controllable complex trajectories or coupler curves generated by relatively simple bar linkage systems
Skin explorations

Surface or skin has always been a major intent of this project. I intend any such kinetic system to be thin across its section or have a thickness to surface area ratio that approximated that of paper or fabric. I began by looking at surfaces that could be manipulated into curved or shaped forms. Paper, fabric, woven-metal screens and other materials basically approximate this quality.

Paper folding

The paper folding and origami like constructions that began with Heinrich Engel provide a valuable look into the problems associated with surface structures and their design. I looked at various methods of folding and strengthening the surface by folding. One characteristic that I specifically looked for was a degree of movement and curvature that could be formed by a repetitive unitized shape. Geometry and form studies of Fuller reinforce the structural integrity of triangulated form. Taking this as a prerequisite for stable structures, I began with the triangle as basic shape. Engel also understood this and goes through a rigorous set of case-studies of various folded triangularized sheet forms. I repeated the Engel studies and looked at them from the viewpoint of their applicability as kinetic structures.

Engel views the fold as a way to control surface stresses and their termination points. He also views his experiments as directly applicable as roof or span methods. In the case of a roof or long span structure the stability and rigidity is made easier by the fact that they are assumed to be stationary. The design and conception also takes this to be a given. The amount of stress on a given stationary object-form like Engel’s are also designed to terminate at stationary points. This makes the calculation and prediction of loads relatively simple.

Engel’s folded forms begin with repetitive unitized order and a diagonal triangulation. He then begins to make more successive folds and triangulations which subdivide the form into a composition of smaller triangular folds.

4 divisions, 8 diagonals

8 divisions, 16 diagonals

16 divisions, 32 diagonals
Each triangulation creates a new point whereby the stresses or loads can be distributed. In this way the total load of the form is minimized as it is distributed over many points. This works the same way a board of nails distributes load over many nails instead of a few.

When a paper folded form is torqued out of total planar unison, arbitrary stresses begin to generate at unpredictable points. These points stress, strain, and tear at the form.

The repeated stresses generated over multiple bends and torques eventually cause the structure to lose all its structural integrity.

It is exactly this kind of motion that I am designing for. In a kinetic surface structure these stresses will appear repeatedly and unpredictably. At these points of pressure only extending surface area can compensate for the stress. Stretching form.

**Folds and resolution**

One of the interesting parts of Engel's paper folds is that they build on each other with complexity. If taken to extremes the successive folding will begin to create yet another flat surface. Like a Serpenski gasket, the folds can be multiplied over a hypothetically large surface and reach a state of smaller but again relative flatness.
Surface-ness and Form

Here we begin to see that surface-ness and form can be seen as a function of resolution. When we think of structural form in architectural terms we begin thinking at a macro level of existence. We commonly design structure to exist at this level because of our macro scale. We do not design for multi scalar strength. A dynamic surface form must have inherent structural integrity. To have structural integrity it has to have multi-scalar strength. For this we have to look to the kernel of its form.

Scale-less form

A scale-less form is a form that can exist at multiple levels of recognition. It is structurally recursive; that is, the larger total form is a concentric scaled version of the same smaller forms. This form when extended into three dimensions can be either a recursive surface or recursive form.

Recursive surface-ness and recursive forms

Recursive surface-ness is a repetitive fractal pattern that exists in a surface form but does not scale up as the same three-dimensional form, as in bee honeycomb. A recursive form is a form that encloses recursive representations of itself within it and represents a larger version of the same form, as in the Serpenski gasket.

Recursive surface forms such as honeycombs and fractalized patterns all exist at a surface level. Most recursively scalable forms like the Geodesic spheres and domes do not allow surface deformation and movement. They work like a Serpenski gasket. Structural integrity is maintained solely by hierarchical recursive scaling. This gives the form total structural integrity at multiple scales but locks it into a scaled up representation of its seed form.

The same series can be created with square folds, but the level of curvature is not as good as a triangulated surface.
**Triangles and resolution**

Triangles retain a kind of ratio of acceptable rigidity to deformation. They can also be easily scaled up and down. In a recursive surface like a triangulated surface form, stresses are forced into direct lines that terminate at controlled points as in the vertex of each triangle. Though a square patterned surface can also be scaled up and down easily, when you begin to torque it out of planar unison, the stresses that form begin to appear across the diagonals of each far vertex as well as adjacent vertexes. This begins to slowly deform each square and bend it diagonally across its face into two triangles. This gives rationality to using a triangular patterned surface for any surface that will bend into three-dimensions rather than a square patterned surface. It also spreads out the stresses across many points rather than a few.

The higher the resolution of the surface pattern, the more curvature or bending the surface can sustain.

**Surface extension and three-dimensions**

A repetitive patterned surface like honeycomb can only be extended in a planar direction. If you create a three-dimensional version or rhombic dodecahedron it can be extended.

The same can be said of triangles. They can be butted against each other to form tetrahedrons and extend indefinitely in three-dimensions. But they can do this with a degree of inherent stability not afforded any other form.
Curved Shells and Hyperbolic Paraboloids

Curved Shell and hyperbolic paraboloid structures all have to maintain surface tension or rigid form of internal tension to be a structure. Without this tension the structure begins to distort and fail. Hyperbolic paraboloid structures are based on the inherent strength of the form and its ability to move the stresses from the surfaces back to the ground plane. The sharper the curve the better the resistance the form has against downward stresses. This works much the same way a cylindrical barrel vault does.

These structures are very stable in a numerous configurations but will obviously fail in motion. If a structure such as the hyperbolic paraboloid could be designed from the standpoint of scale-less dynamic structure what would be its constraints?
Section-surface model and plan, section and elevation of Hyperbolic paraboloid form.

Computer visualization of a curved surface form showing triangulation as means of curvature.

Diatom. Triceratium alternans. Magnified 1900:1
Crossing patterns and stretching

For a surface to create smooth curvature it must be able to expand in surface area as a piece of fabric would when stretched and twisted. Multiple member configuration patterns can designed for different forms of stresses such as stretching or expanding surface area.

A vertical stress or stretching pattern (fig. 1) can force stretching and curvature in one direction.

A two way pattern (fig. 2) allows stretching in two directions but less curvature because of the opposing diagonal members.

A diagonally crossed pattern allows two-way stretching and curvature (fig. 3).

The number of members at each node, diagonal pattern direction, and overall regularization of nodes all contribute to a pattern's ability to form smooth curvature.

Obviously there are many possible configurations of crossing patterns that decompose into triangles but I have shown only three to show the possible ways to control stretching in different directions. For two-way stretching and curvature a one way diagonal pattern works best. Interestingly this is the same method many three-dimensional modeling programs use to generate smooth curved surfaces. (fig. 00)
One way stretching pattern

Two way stretching pattern

Two way stretching pattern with curvature
Kinetic wall

Scale-less form. Scale-less structure.

The prototypes represent an attempt to synthesize ideas of scalability, motion-control and form into a few working physical-prototypes. Each prototype progressively moves towards control and movement of a larger dynamic surface form.

The structure is basically an assembly of one primary cell design. Each ‘cell’ is a grouping of three equal sized members that form a equalaterial triangle. A larger hexagonal unit of comprised of six triangles grouped together around a central mast, which forms a ‘panel’ unit. As more panels are added, the grouping forms a kind of structural bay. As more bays are added a surface begins to form.

The masts of each panel are held in perpendicular intersection at the center point by a set of cables that terminate at the edge vertices of each cell. Additionally they are held in tension by a series of springs that force it into an angled position in relation to the next panel.

To facilitate motion, a cable is strung along the back of the two vertical members formed by each cell. This cable begins at the top vertex of each hexagonal panel and runs through the top of the panel’s mast and then back down the adjacent vertical members of each preceding cell.

This configuration allows individual control of each panel in relation to the adjacent panel. It also affords the ability to add more panels to create larger total surfaces.

In this way a controllable dynamic surface skin is formed. Control is achieved by a series of computer controlled servos that control each cable.

Computer control is necessary to control the total movement and configuration of the surface. For a large surface as many as twenty-four servo-mechanisms are needed.
One bay prototype

The one bay version demonstrates controlled movement across three main panels. Form and motion are the primary concerns.

Two bay prototype

The two bay version explores the relationship of adjacent bays and form and movement across six panels. Skin or surface is proposed as a membrane or fabric to cover the structure.

Cables, Actuators and Control Methods

Three separate servo-motors actuate each cable and are located below the base of each prototype. The servo-motors are controlled by a servo control device which is in turn controlled by a computer based control interface. Each servo controls the rotation of one panel. A controlled curvature can be created by activating all three servo-mechanisms in unison.

A continuous skin or surface can be attached to the prototype creating an continuous surface quality. Mechanics are inside the form and the skin is a separate external surface.

Design goals for kinetic wall prototypes:

acceptable ratio of thickness to total surface area
scale-less rigidity of form
means of motion / actuation
computer control of actuators
Diagram of control and movement of kinetic wall system

Motorized Base

Wall Structure

Four Bay Prototype

control program

computer

actuator controller

actuator

structure-form
Diagram of control and movement of kinetic wall system with sensory feedback system

"Smart" node control program

computer

actuator controller

actuator

sensor

structure-form
Computational integration and control

Integrated computer control is ideally done with an advanced system of positional sensor devices or similar devices. Control is based on a feedback loop system. (Diagram 2)

Current prototypes are constructed with only one way positional servo control. (Diagram 1) This prototype is essentially a Level II machine or a machine that exhibits multiple degrees of control and movement, but is still essentially human controlled via a computer interface and control system.

With the addition of a fully integrated sensor system, the system can gain the sophistication of a Level IV machine and become a truly dynamic wall system.

1 A level one machine can be described as a simple tool, lever, wheel, or cam. A level II machine can be described as a systematized version of a level I machine such as a bicycle, a sewing machine, or farm machinery.

2 A level IV machine is described as a machine that has multivariable, automatic control, coupled with a heuristic or learning capacity, such as an auto-focusing system, developmental artificial limbs, or expert-systems used to control the wing and surface of fighter-jets.
Potential Uses

An architectural kinetic surface such as the Kinetic wall prototype can be developed as a piece of architectural ‘hardware’. It can be used at three scales: small (interior space device fig.1), medium (new building surface fig.2), or large (dynamic roof structure fig.3).

This system is mobile and can be controlled by either an active computer control system or by direct human movement.

In the case of computer control it is envisioned that either a set of pre-programmed configurations can be the form generator or a minimal and maximal range of form can be set and the control program will control the form within these parameters.

For direct manual control the control program can be set to allow free movement within various set parameters. This will effectively let the users or occupants actively control the form of the kinetic wall.

In this fashion, the kinetic wall can respond to any number of human and environment generated variables: sun, wind, shade, light, shadow, whim, desire or impulse.

This project has always been an exploration of sorts. It is an incomplete project that only opens more doors than it closes. The idea of smooth dynamic surface form and its generation are novel for me only if the form is active. This is the transformation of static to liquid.
Design:


Structures:


Materials:


Kinematics / Mechanisms

Brown, Henry T. *Five hundred and seven mechanical movements: embracing all those which are most important in dynamics, hydraulics, hydrostatics, pneumatics, steam engines, mill and other gearing, presses, horology, and miscellaneous machinery, and including many movements never before published and several which have only recently come into use*. 18th ed. New York: Brown & Seward, 1896.


Computation:


4 divisions, 32 triangular surfaces
8 divisions, 128 triangular surfaces