The Design and Construction of Interactive Architectural Environments

The Digital Mile, Zaragoza, Spain

by

Shutsu K. Chai

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ABSTRACT

As a part of a master plan for the Digital Mile, a park in Zaragoza, Spain, this thesis will undertake the mechanical design and construction of a responsive and rearrangable system of walls and doors for increasing the flexibility of the "edge" between open space and a new museum building. In order to study this question, this thesis builds on a previous planning thesis and the prescribed architectural forms as a basis for investigation of potential construction materials and joint technologies. Through this study, a design will emerge for this unique system that allows space to expand and contract and the building edge to become porous or sealed, responding to the demands for different activities and situations. Construction materials and mechanisms will be studied based on the functional requirements of the system. These investigations will lead to recommendations for mechanical means to achieve the prescribed architectural and performance specifications. It is anticipated that this new building-edge will support a wider variety of activities and in this way enhance the livability and usability of public space. Beyond the physical design, this thesis will also demonstrate the ability of interdisciplinary work to enrich the design process.

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1. Introduction

The Department of Urban Studies and Planning at MIT has been given the opportunity to develop a proposal for a new park in Zaragoza, Spain[1] called the Digital Mile. As a part of that proposed master plan, this thesis will develop the urban and mechanical design of a reprogrammable museum building "edge."

Located in the northeastern part of central Spain and in close proximity to the Mediterranean Sea, the city has a maritime climate with mild winters and summers (Figure 1).[2] The city is an industrial and trade center as well as a busy railway junction, annually hosting the National Trade Fair.[3] Given the various social and business activities of Zaragoza and its mild climate, the outdoor open spaces are an important part of the city.

Figure 1. Map of Spain, Zaragoza in Northeast[4]

Public spaces and the events that occur within these spaces are an integral part of the city's identity.[5] Public spaces create places for markets, community gatherings, business transactions, tourist attractions, art and public performances, drawing people together for a myriad of purposes. As such, public spaces can help make a city distinct

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[1] Zaragoza is the capital city of the former kingdom of Aragon. In the last two millennia, Zaragoza has passed through many hands, most notably Roman and Moorish rule; even today, Roman and Islamic architecture remain part of the city. ["Zaragoza" (2005). Encyclopedia Britannica Online, Encyclopedia Britannica.]

[2] "Spain" (2005). Encyclopedia Britannica Online, Encyclopedia Britannica.

[3] "Zaragoza" (2005). Encyclopedia Britannica Online, Encyclopedia Britannica.

[4] Factbook, The World (2005). Map of Spain. The World Factbook. C. I. Agency, Central Intelligence Agency: Map of Spain.

[5] "A New Book on 'Event Places': Designing More Effective Public Spaces." PLAN, MIT School of Architecture and Planning **Volume**, DOI:

and viable because they draw residents and visitors alike. Therefore, careful design of public spaces and their associated events are critical pieces of any urban design.

With the introduction of Spain's newest high-speed train AVE to Zaragoza in the spring of 2004, the mile-long stretch of land that the former railway corridor occupied was made available to become a mile-long area for development, public facilities and open spaces dubbed "The Digital Mile" (Figure 2).[6] The Digital Mile will be a unique public space because it will be linked by wireless internet access for computers, or in other words, information access. In addition to creating information accessible places, the park will also include an identifiable and attractive museum building front that is responsive to and functional for a variety of groups and activities (Figure 3).[7]

Figure 2. Urban Design Concept: The Digital Mile

[6] "AVE Spain High-Speed Rail Network, Spain." Retrieved November 28, 2005, from http://www.railway-technology.com/projects/spain/.

[7] The museum type is also still undefined at this time. Potentially, the use may respond to the design rather than demanding the design to respond to the museum type.

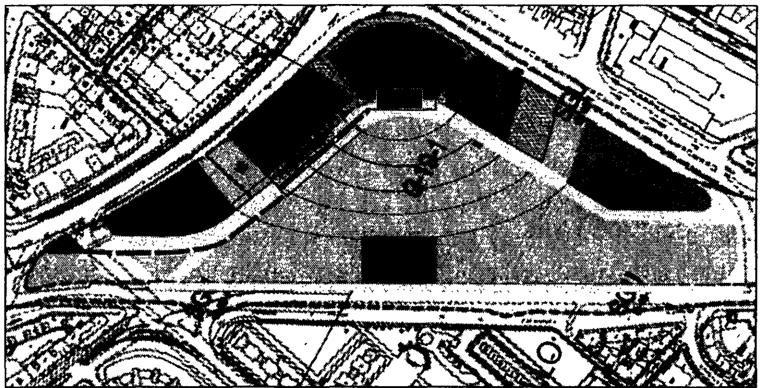

Figure 3. Musuem Building, Second from Left.[8]

In order for space to be both responsive and functional, it must also be flexible in its openness to the public. Yet, spaces whether public or private are frequently defined by fixed boundaries such as walls and fences, leaving little ambiguity about where inside begins and outside ends. The Digital Mile will try to capture ambiguity in the design of the front of its museum building to improve the versatility of the space. The design for the front will be both open and accessible – as is its wireless network. To accomplish the objectives of openness and accessibility, this thesis will study and develop a system of movable walls and doors that blur the boundaries between what is inside and what is outside and allow the building edge to permeate the open space around it. Figure 4, created by Professor Dennis Frenchman is an example of what such a system might be with a system of doors that can rotate into a set of arrangements (Figure 4).[9]

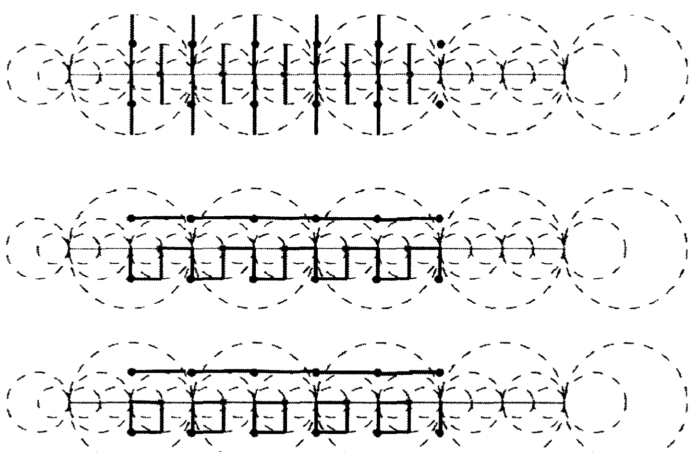

Figure 4. Potential configurations of doors based on a fractal

[8] Frenchman, Dennis (2005). Layers of Media Video Conference 4. Cambridge, Massachusetts Institute of Technology: 40.
[9] Ibid.

Several specific functional requirements have been set at this time relating to usage and size constraints. The rearrangement of parts will likely occur several times a day, or at least on a daily basis. Thus, the design must be simple enough to move frequently and in short periods of time. As this system will be a part of the building edge, the ability to seal off the building edge and to be weather resistant will be important characteristics. While not necessary in the climate of Zaragoza, the possibility of thermal insulation and air conditioning may prove useful for implementation at other sites. Finally, the geometric requirements of this system will be a height of 30 feet, a length of 100 feet, extending 30 feet into and 30 feet out of the building.

Through exploring existing examples of responsive architecture, further design criteria can be established for the building edge. These criteria will focus on the specific uses and flexibility required. The optimal arrangement and function of this system will emerge from those criteria. Once the optimal arrangement or arrangements and functions are established, this study will focus on developing the plans for a more detailed mechanical design for the actual construction of the system. This process will include material selection and the joint technologies necessary for the movable parts to function.

The next section reviews existing examples of kinetic architecture in order to provide a starting point for this study. Next, a set of design criteria are developed for the project. Finally, through modeling, an actual responsive system will be designed and engineered.

2. Background

Portable architecture and deployable structures have been present throughout history in different forms. Many everyday examples exist, including something as simple as a tent or mobile home to forms as complicated as the retractable stadium dome at Minute Maid Park. From the tent to the mobile home to the retractable stadium dome, many everyday examples exist. In the evolution of architecture, these structures have gained complexity and grown increasingly innovative. Portable and flexible elements allow the transport or alteration of environments, and the advantages associated with this type of architecture are a result of the flexibility to accommodate to different sites, functions, activities and needs.[10]

2.1 Kinetic Typologies

There are four distinct kinetic typologies: pneumatics, pantographs, structural fabrics, and hinges or sliding elements. More specifically, these four typologies are a combination of deployable and portable structures. The unfolding nature of deployable architecture allows a small collapsed system to expand into a significantly larger structure. Portable structures are completely transportable structures. Pantographs are hinged struts that can expand and contract; for example, Figure 5 shows the Hoberman Arch designed by Chuck Hoberman (Figure 5). Looking at just a small portion of the whole, the struts rotate at the hinges allowing the pantograph to extend and draw back (Figure 6). Pneumatic structures such as Airtecture Hall, are easily transported and erected inflatable buildings (Figure 7). A simpler example is a moon bounce, a structure that is often seen at traveling carnivals. Structural fabrics, which are lightweight and flexible, include structures as commonplace as tents. Finally, hinges, sliding elements and other moving joints permit and guide movement. Examples include door hinges and sliding windows. The potential designs for this project will deal with one or a combination of these typologies; the structures may combine the ability to deploy or unfold with the ability to move and rearrange. While pneumatic structures are useful for their simplicity of erection, this research will exclude pneumatics.

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[10] Kronenburg, Robert (2003). Portable Architecture. Oxford, Elsevier/Architectural Press.

Figure 5. Hoberman Arch[11]

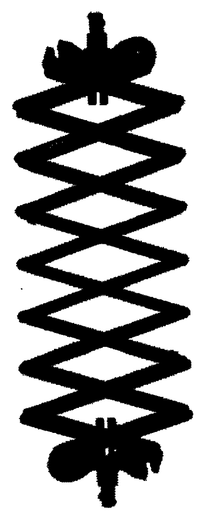

Figure 6. Pantograph[12]

[11] Barista, Dave (2001). "Retractable Arch Will Star at Olympics." <u>Building Design and Construction</u> **42**(12): 1.
[12] International, Bowens (2005). Lightlift Pantograph. **400x400 Pixels**.

Figure 7. Airtecture Hall[13]

2.2 History of Deployable and Kinetic Environments

In the field of deployable and kinetic structures, significant research has been done on the form that these structures should take and how best to design the various parts for the intended kinetic functions. Several leading researchers in this field include: Korio Miura from Japan, Mamoru Kawaguchi from Hosei University, Felix Escrig from the University of Seville, Waclaw Zalewski from the Massachusetts Institute of Technology, and The Deployable Structures Laboratory at the University of Cambridge.[14]

Beyond the bare mechanics of these structures, other researchers and designers have sought to make these structures art forms that respond in design to nature, beauty and usage requirements. Chuck Hoberman is also a prominent inventor of deployable structures, but with a greater focus of the structures for art rather than architecture.[15] For Santiago Calatrava, forms in nature, particularly human form, provide the ideal prototypes for the overall design of kinetic architecture.[16] The Archigram group, led by Peter Cook, were visionaries of portable, kinetic and reprogrammable architecture that give the user the power to transform and adapt their own buildings, communities and cities.[17]

With growing demands for versatile building structures in the last 30 years, architects and engineers have joined together to develop innovative solutions to respond. Simple examples of reprogrammable space include doors and room partitions. Gunter Henn designed the KonzenForum for Volkswagon with two sets of six 60-foot-high glass doors that function like vertical blinds, opening the space for natural ventilation and an

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[13] BauNetz Airtecture Hall.
[14] Gantes, Charis J. (2001). Deployable Structures: Analysis and Design. Southampton, Boston, WIT Press.
[15] Ibid.
[16] Adda, Catherine (2000). Santiago Calatrava "God Does Not Throw Dice". L. F. D'ici. Zurich, Sehfield Film and TV Producktionen AG.
[17] Cook, Peter, Ed. (1973). Archigram. New York, Praeger Publishers, Inc.

"indoor piazza."[18] Another more complex example is the Mobile Classroom Project by FTL Design Engineering Studio and Todd Dolland. This project includes a set of unfolding walls to expand the enclosed space from a 1.5 meter long trailer to a 50 square meter classroom, thus allowing ease in transportation when folded and ease in erecting the structure as the process is simply unfolding the trailer.[19] A third example is Lightweight Structures Unit and Arena Seating's mobile canopy system that consists of a cantilevered arch that is raised and lowered with a winch.[20] Flexible and made of lightweight materials, aluminum with a membrane stretched across, and this canopy is versatile and easily portable.[21] In another relevant model, the Bristol Development Corporation Marketing Center, the building structure is folded into a large mast which expands like an upside-down umbrella after the base of the mast is secured in the ground.[22]

2.3 Materials

The potential designs for this building edge depend on available materials, their properties, and the ability of the material to meet the functionality that the design criteria require. Industrial and natural are two broad groupings for these materials. There are four major families of industrial materials: metals, polymers, ceramics and composites.[23] From those broad industrial categories and natural materials, this investigation will focus on those materials that are useful to kinetic architecture, namely those that are lightweight while still having significant strength. In addition, weather resistance will also be essential to the design of this system as portions of this system may be exterior to the museum building.

Important material properties include ductility, malleability, density, strength, elasticity, durability and weather resistance. Ductility refers to the ease of a material to be drawn into a wire or flattened into a sheet. Malleable materials are easily workable. Density is measured in weight per volume, and consequently provides a relative measure of weight. Strength is typically assessed by a measure of the compressive and tensile strength that a material can withstand.[24] Elasticity is a measure of how much a material can deform elastically, or in other words, deform without permanently deforming.[25] Ideally, the structure will be lightweight so that it will be easily moved. Potentially, flexibility may add another element to the capabilities of the system.

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[18] Weber-Hof, Claudine (2000). "Autostadt Wolfsburg, Germany; Gunter Henn's Corporate Theme Park for Volkswagen Engages Modern Architecture to Celebrate the Realm of Product Branding." Architectural Record **188**(11): 148.

[19] Kronenburg, Robert (2003). Portable Architecture. Oxford, Elsevier/Architectural Press.

[20] Ibid.

[21] Ibid.

[22] Ibid.

[23] Fernandez, John (2006). Material Architecture: emergent materials for innovative buildings and ecological construction. Boston, Architectural Press.

[24] Ibid.

[25] For example, a rubber band deforms elastically when it is stretched and returns to its original shape when the force is released. In contrast, taffy stretches and is permanently deformed.

2.3.1 Metals

In the family of metals, there are two large categories: ferrous and non-ferrous, or in other words, iron-bearing and non-iron-bearing. Important characteristics of metals relevant to this project include ductility, high strength, hardness and durability. Steel and especially stainless steel are key ferrous metals used for structural situations. Cast irons may also be utilized for smaller and shorter components such as bearing plates. The primary difference between steel and cast irons is their carbon content, where higher carbon content increases strength but decreases ductility. Stainless steels contain at least 10.5 percent chromium; this metal addition and the addition of copper, nickel, titanium, silicon, molybdenum, aluminum, nitrogen and sulfur contribute to the corrosion resistance of stainless steel.[26]

Aluminum, copper and zinc are common non-ferrous metals that are possible construction materials. The 6000 series of aluminum are considered the architectural alloys and can be used for structural elements. Aluminum is considered a light metal with good strength and stiffness relative to its weight in addition to a low density. Copper and zinc sheeting and their alloys of bronze and brass are also useful metals because of their ductility and capability of enduring more wear. Copper has a particularly high ductility and mechanical workability. All three metals—aluminum, copper and zinc—are also corrosion resistant, a characteristic essential to enduring varying weather conditions.[27]

2.3.2 Polymers

Polymers are long chains of small molecules called monomers. Because of length of these chains, polymer properties are largely dependent up the arrangement of those chains and interactions between those chains and their subparts (Picture p.162). The three primary categories of polymers are thermoplastics, thermosets and elastomers. Thermoplastics are those plastics that can be recycled, or in other words, melted and reformed repeatedly; their polymer chains are not chemically bonded and thus, can slide with respect to one another when heated. The structure of thermosets with cross-linking between chains and parts of chains cannot undergo the same process of reformation as the bonds prevent themosets from returning to a liquid state. The relevant thermosets are epoxy resins which will be discussed later in the composites section. Between a solid and a liquid, elastomers exhibit elastic elongation 300%-800% its original length.[28]

Transparent thermoplastics often serve as lighter weight substitutes for glass. Polycarbonate (PC) is a common glass substitute that is hard, durable and UV resistant, but subject to scratching and moisture damage. Ethylenetetrafluroethylene (ETFE) is another common glass substitute, but unlike PC, ETFE is non-rigid and thus, must be held in tension. ETFE is also UV resistant and strong in tension and is generally used to infill an area.[29]

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[26] Fernandez, John (2005). Meeting with Professor Fernandez. S. Chai. Cambridge: Materials survey with Professor Fernandez. .
[27] Ibid.
[28] Fernandez, John (2006). Material Architecture: emergent materials for innovative buildings and ecological construction. Boston, Architectural Press.
[29] Fernandez, John (2005). Meeting with Professor Fernandez. S. Chai. Cambridge: Materials survey with Professor Fernandez. .

Nylons are also key thermoplastics. Nylon 6 is a flame resistant material, a beneficial characteristic. Ripstop nylon is made of a heavy thread in an approximately half centimeter grid and is thus durable and difficult to rip. Because of its strength and durability, this nylon is useful outdoors in places with strong winds; large kite-makers in Japan often use this material because of its strength and ability to withstand substantial ripping.[30]

Several thermoplastics can be used as non-rigid fibers in structural fabrics. Polyethylene (PE) and polypropylene (PP) are the two most produced synthetic polymers that can be used as structural fabrics. Polyurethane (PUR) and Polyvinyl chloride (PVC) can be used as Teflon coated structural fabrics. Aramid fibers such as Kevlar are useful for reinforcing composites.[31]

The last two categories, thermosets and elastomers, have fewer relevant materials. The thermosets of interest are epoxy resins which will be discussed later as a part of the composites section. Important elastomers in kinetic architecture are the silicones which are inorganic polymers. Useful characteristics of silicones include resistance to chemicals, oxidation and water, stability at high temperatures, non-conductance and high elasticity.[32]

2.3.2 Ceramics

Ceramics are brittle and hard materials which can be classified as vitreous, glass, stone and concrete. Stone will not be considered as they are too heavy and dense for a kinetic system. Vitreous ceramics are fired metal minerals such as bricks or tiles. The most common glass is made of soda lime silica. Concrete is a mixture of cement, water and different sized aggregates.[33]

Glass is a particularly interesting material given its light transmission properties and existing glass technologies that allow the properties of glass to change on demand. Given that ability to change, glass has the potential to further increase the flexibility and reprogrammability of the museum building edge.

Glass is a super-cooled liquid derived from the fusion of silicon, boron, germanium, phosphorus and arsenic oxides cooled to a rigid state without crystallizing.[34] The lack of a crystalline structure permits light rays to pass through glass without scattering while still absorbing ultraviolet radiation of wavelengths less than 315nm and greater than 3000nm.[35] Glass has high strength and hardness, but cannot plastically deform and is consequently very brittle with a low tensile strength.[36] The appearance and thermal properties of glass can be changed through coatings, sandwiched layers, added impurities and actuated changes in its crystalline structure.

Actuated changes in glass are particularly important for this research as this potentially adds another layer of responsiveness and changeability to the system. There

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[30] Ibid.
[31] Ibid.
[32] Ibid.
[33] Fernandez, John (2006). Material Architecture: emergent materials for innovative buildings and ecological construction. Boston, Architectural Press.
[34] Compagno, Andrea (1995). Intelligent Glass Façades: Material, Practice, Design. Berlin, Birkhäuser Verlag.
[35] Ibid.
[36] Ibid.

are glass types and sandwiched layers that vary in color and transparency with light, temperature, and applied voltages which can be exploited in this study.[37] In addition, laminated glass can also be used with a structural fabric where the sandwiched fabric is used to hang the glass.[38]

Of the different types of concrete, aerated autoclaved concrete (AAC) is of interest for kinetic architecture because of its light weight and strength. AAC is essentially a foamed concrete with a cellular structure, a structure similar to a sponge dipped in plaster. AAC's cellular structure allows the material to be light weight and thus easily moved. Typically in the form of panels, blocks or long slabs, AAC is generally used as a rigid core rather than as a stand-alone panel or block as concrete is prone to chipping.[39]

Ductal is an ultra high performance concrete known for its ductility and high strength. This fiber-reinforced material is capable of significant bending before fracture.[40] In addition, Ductal is capable of withstanding 200MPa of compressive force and 40MPa tensile force. Ductal's durability and resistance to environmental "attack" also make Ductal a useful material to consider for this reprogrammable system.[41]

2.3.3 Composites

Composites are formed of combinations of the above materials. While there are many types of composites, this study will limit the considered composites to pultrusions, a fiber reinforced polymer. Pultrusions are made of fibers pulled through an epoxy resin and then through a die that shapes the fibers.[42] Listed in order of increasing strength and cost, carbon, aramid or Kevlar and E-glass fibers are used to create pultrusions.[43] Compared to wood and metal products, pultrusions are more corrosion resistant and light weight, two characteristics important for this outdoor kinetic system.[44] In addition, nearly any shape with a constant cross-section can be pultruded.[45]

2.3.4 Natural Materials

Natural materials, unlike industrial materials, require less processing and thus create more savings on the production side. Relevant natural materials include bamboo, wood and natural fibers. While bamboo is stronger than steel and significantly more lightweight, the difficulty and cost of acquiring bamboo in Spain leads this study to exclude bamboo from consideration. Wood is a biomaterial that has been used in building from the earliest structures and can be used as a structural material. Natural fibers include straw, flax, jute and sisal; these fibers are used in fabrics when woven

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[37] Ibid.
[38] Fernandez, John (2005). Meeting with Professor Fernandez. S. Chai. Cambridge: Materials survey with Professor Fernandez. .
[39] Ibid.
[40] Ibid.
[41] Lafarge, Bouygues. (2002). "Ductal." Retrieved December 13, 2005, from http://www.ductal.com.
[42] Fernandez, John (2005). Meeting with Professor Fernandez. S. Chai. Cambridge: Materials survey with Professor Fernandez. .
[43] Ibid.
[44] Creative Pultrusions, Inc. (2002). ""The World's Most Innovative Leader in The Fiber Reinforced Polymer Composites Industry." ".
[45] Strongwell. (2005). "Pultruded Products." Retrieved December 13, 2005, from http://www.strongwell.com/PultrudedProducts/Custom.htm.

together. Fabrics may be a useful flexible and lightweight material for use as part of the kinetic elements in this study.

2.4 Mechanisms

Mechanisms are an integral component of this study as movement is what makes this building edge digital and thus, makes this new building-edge a compelling part of The Digital Mile. Where digital is defined by open access and discreet elements, the reprogrammable aspect of this building-edge is the primary link to the rest of The Digital Mile. Rearranging the partitioning walls will create a set of unique configurations while the flexibility of space will permit the museum front to be open and accessible. Thus, the importance of movement to this system demands careful design and selection of the mechanisms.

Through a survey of general mechanism categories, this thesis will develop a better understanding of what motions will be mechanically feasible and how to begin designing the mechanisms to control and create desired movement. There will be multiple ways of achieving any general type of movement, but those designs will be narrowed down to those that best support the functional requirements of this building-edge. Machines are generally used to aid in repetitive actions or to facilitate tasks that are difficult or impossible to accomplish manually. This section will survey mechanisms that permit these motions, including repetitive, intermittent, reversing, reciprocating, differential and straight-line motions. In addition, this survey will also touch on stopping, hydraulic and automatic feeding mechanisms.

Repetitive motions are a key element in this project; elements of this system must be able to move many times, and often in the same way from day to day, hour to hour, or in other words rearrangeable and reprogrammable. Cams are mechanisms that are used for elements that revolve, oscillate or slide, where the cam is a rotating element that has edges and grooves that impart a motion to a follower. Cams allow the follower to repeatedly travel in variable and complex paths as the cam rotates. A common example..

Intermittent motions are a subcategory of repetitive motions, but involve a pause between repeated motions. As the walls of this building edge will be stationary for stretches of time, periods of movement are intermittent. Although the overall movement is intermittent, the application of an intermittent mechanism is more relevant to the study of how to introduce precision to the placement of moving elements. The most basic example of a mechanism that imparts intermittent motions is the ratchet gear, much like a notched cam, where a follower encounters gradual movement and sudden pauses. A particularly useful mechanism for intermittent motions would be the Geneva wheel, a mechanism often used on machine tools to rotate a part of the machine through a fraction of a revolution.[46]

Differential mechanisms allow precise movements as differential motion is the "resultant or difference between two original motions."[47] This differential resultant can be precise at values significantly smaller than the original motions, thus allowing for more precise movements. A good example of a differential mechanism is the differential screw. A differential screw has two sections of threads at different pitches. The resulting

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[46] Jones, Franklin D., Ed. (1930). Ingenious Mechanisms: Volume 1. Ingenious Mechanisms For Designers and Inventors. New York, Industrial Press Inc.
[47] Ibid.

differential motion is the difference between the two pitches, allowing for a slight motion without using a very fine pitch or weak thread.[48] As the armature of this building edge is shifted from location to location to reconfigure the open space, the precision in placing each kinetic element will be important. For example, if a configuration is supposed to create walls that form a rectangular room, if the corners are not right angles, the usefulness of the space is compromised; tables may not fit into corners where the angle is less than ninety degrees.

Reversing motions are needed to retract elements, particularly those elements that travel linearly. While this system may involve hinged, rotating elements, this system may also potentially involve elements traversing the entire open space. With elements that may need to move from one end of the space to the other, the reverse, or returning motion is equally as important as the initial forward motion.

Reciprocating motions are those that translate rectilinear motion to rotational motion or vice versa.[49] This translation may be needed to drive movement from a single location while the elements of the system reach far beyond the mechanism's actuator. A good, simple example of this would be a rack and pinion set-up, with a small rotating gear, or pinion, moving on a flattened gear called a rack. Here, the rack translates the rotational motion from the motor and pinion into linear movement. This may be useful concept, where a rotational actuator drives linear movement, as either the actuator with the kinetic element attached can move along a rack, or the rack can be extended from a fixed actuator.

Stopping mechanisms will be a key component of this system; whatever object is moved from one point must be stopped at another and fixed there. There are two types of stopping mechanisms: one stops only once and must be reset again by hand, and the other can trip again and again periodically or at regular intervals.[50] The latter type is of greater interest, as this reprogrammable system should be automated and not require manual resetting. For these mechanical tripping mechanisms, there are three methods: clutches, shifting belts, and disengagement gearing. A clutch as a stopping mechanism separates a driving member, or the source of power, from a driven member. Belts are shifted generally to control an entire machine's start or stop. Gears that engage and disengage are also capable of starting and stopping a machine or object. Selecting stopping mechanisms requires consideration of the speed of the moving objects, their inertia, and other factors such as how much shock the set-up can withstand.[51] In addition to mechanical tripping mechanisms, there are also electronic tripping mechanisms; generally electronic tripping mechanisms are used only when they simplify a mechanical mechanism.[52]

Finally, there are hydraulic transmissions and automatic feeding mechanisms which may have a limited relevance to this project. Hydraulic operation of machines has several advantages over mechanical operation including quiet operation, lower power consumption, fewer moving parts, and fewer wearing parts, resulting in greater reliability

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[48] Ibid.
[49] Ibid.
[50] Ibid.
[51] Ibid.
[52] Ibid.

and lower maintenance and operation costs.[53] Automatic feeding machines are not intuitively relevant, but this building edge will likely make use of several if not many of the same element. Consequently, although automatic feeding is typically applied to feeding parts to a machine in the manufacturing or machining process, some of the underlying concepts for managing multiple identical elements may be applicable.

[53] Ibid.

3. Methodology

This project is divided into three stages: investigation of the problem and program definition; architectural design; and mechanical design. Investigation of the problem or architectural program is essentially defining what types of uses and activities that the building-edge will need to support. Architectural design outlines what general form the building-edge should take to meet needs of the architectural program. Mechanical design focuses on how to build the architectural design, including the construction materials and the mechanisms that will allow movement and reprogramming of the system.

The focus of this thesis will be the last stage of mechanical design. The first two stages have already been completed in a separate planning thesis; the methodology of the first two sections are included in Appendix E. The most promising approaches from the first two stages will be investigated in more detail in this engineering thesis through a focus on mechanical design. Through evaluating designs against the set of functional and performance requirements, the best architectural form will emerge, setting the stage for the in-depth research of the mechanical elements of the system.

Once the architectural design ideas have been assessed and the one or two best ideas have been selected, the mechanical design of the system can begin. Following the investigation of mechanical design, the project will return to a second stage of assessing the proposed architectural forms, but this time with attention to the mechanical feasibility and cost of construction. At this point, the final architectural form will be selected, and the project can enter the final stage of mechanical design in which the mechanisms for the best architectural forms are selected and designed with even greater detail.

The mechanical engineering research investigates the kinetic typologies and materials that this responsive environment requires, and in this way, this thesis also articulates a design methodology for kinetic architecture. Through looking at relevant examples of other types of kinetic and portable architecture and deployable structures, a toolkit is developed containing mechanical and architectural elements that can be used as portions of the kinetic system. By using this toolkit as a starting point. the mechanics and architecture evolve and take their own form.

Next, design of the mechanical system will respond to the functional requirements through the materials selection process and design of necessary mechanisms for movement. 3D computer modeling will also aid the understanding of the kinematics of the proposed solutions. Ultimately, this project consists of two parallel design tracks at different scales: the macroscopic scale of the building and the mesoscopic scale of the individual components that comprise the kinetic system, the focus of this thesis.

Mechanical Design In-depth

The mechanical design is the smaller scale of design that focuses on how any architectural design idea can physically be built. Drawing from the movement requirements of the architectural design, the functions of the kinetic system are defined. The definition of function leads into two parallel tracks: mechanisms and materials. The mechanisms track explores the potential joint and movement technologies required to move elements of the building edge. The materials investigation involves the assessment and selection of the relevant materials that support the functional requirements of this flexible building edge.

The exploration of function draws on the definition of the architectural program, or in other words, function outlines the general armature movements that will support activities in this space. For example, there are several potential options for the function definition of a window: sliding up and down; swinging in and out, attached to the building at the top; and swinging in and out, attached to the building at the side. Defining the functions of this system ultimately amounts to movements and characteristics necessary to achieve the architectural program. More broad examples of these characteristics include whether components of the system will be suspended, permit movement, or provide a secure building edge.

Investigating the joint and movement technologies brings the study to a still smaller scale, delving in to *how* the functional requirements can be achieved. This portion of the project will proceed through looking at mechanism precedents to identify a set of mechanisms that can be used to move the armature in the desired manner. This process will include the definition of functional requirements of the system such as speed control or strongly fixed positions and the characteristics of the system such as the weight of the elements to be moved. Through a more detailed study of existing mechanisms and their variations, this study will select the most appropriate mechanisms to achieve the reprogrammable building-edge.

The materials selection process addresses both the functional requirements of the larger architectural design and the mechanical design. Proper materials will be important to achieving performance specifications such as weather-proofing, security, digital-projection capabilities, and photo-sensitivity. Carefully selected materials will also affect the usefulness of the system, including moveability of elements, durability of the entire system over time, and robustness of the mechanisms. Materials will be assessed and selected through a program that Professor John Fernandez[54] has helped to develop, the Cambridge Engineering Selector by Granta Design. This program will output a range of potential materials given an input of desired material properties. For the specific functional requirements of the larger system, materials will be carefully selected to achieve those demands.

[54] John Fernandez is a professor in the Department of Architecture at the Massachusetts Institute of Technology. He is also a part of the Building Technology Group, a group comprised of architecture and engineering faculty.

4. Performance Specifications

The performance specifications are an important part of this design thesis; the established specifications will serve as a criteria against which all design proposals will be evaluated. In addition, the performance specifications will demonstrate the capabilities that will distinguish a reprogrammable building-edge from a static one, thus further justifying the need for such an edge. This section will discuss the environmental standards for performance and the measures of usability for design evaluation, the two categories of performance criteria that are relevant to the mechanical design. Further discussion of performance specifications are in Appendix F.

4.1 Environmental Standards

Environmental standards refer to the building edge characteristics that permit the separation of environments. Evaluation will focus on the robustness of that separation. These standards will identify the conditions to which the building-edge will be subject and the system characteristics that will respond to those conditions. This section will discuss the functional requirements that the system will need for this building-edge to meet the needs of a museum as defined by the environmental standards.

4.1.1 Exterior Standards

The exterior of the building edge that will face the outside will have a variety of characteristics that must be met: weather tightness, security, corrosion resistance, UV radiation resistance and non-flammability. Weather tightness shields the interior from weather conditions such as rain or heavy winds, protecting any exhibit materials and providing a sufficient temporary shelter for visitors.[55] Security of the exterior edge is needed for the building as a whole to be secure so that the museum's valuables are protected, especially after hours. This characteristic includes impenetrability of the exterior wall of the building-edge and strongly fixed kinetic elements. Corrosion resistance and UV radiation resistance are both necessary to prevent degradation of the edge as well as for maintaining the security of the building edge over time. A corroded or degraded exterior wall will be much more easily forcefully breached. Lastly, non-flammability is an important feature for protecting a museum, again, as museums generally contain valuable exhibits, and in this case, will likely have expensive technology.

4.1.2 Interior Standards

The interior of the building-edge also has characteristics that may have impact on the importance of this new edge including lighting, the provision of shade, the possibility of air conditioning and access to electricity. Lighting will be important for nighttime activities and daytime events farther from the open edge that is lit by natural light. Lighting is also an important part of exhibits, ensuring that details are visible and focusing on important aspects of a display. The provision of shade permits the interior to be a refuge for park visitors away from the sun. The possibility of air conditioning requires a measure of air tightness within any enclosed space that is created. Although air conditioning may be a bonus, it is not necessary in this moderate climate. Finally,

[55] Snow will not be a concern for the location in Zaragoza, Spain as this is a Mediterranean climate.

electricity is an integral part of the system, and thus, its transmission is a necessity. Without electricity, the different moving elements would not be able to be automated and easily reprogrammed.

4.2 Usage

This section will discuss how the building edge will be used and elements of that usability that will be drawn on for the evaluation of any design proposals. Evaluation will focus on the ease of deployment and use; this section will develop the usability characteristics that will be measured. These characteristics will be: programmability, flexibility, ease of reconfiguration, speed, and user characteristics.

1. Programmability: Programmability refers to the degree of morphological change possible, or in other words the changeability the system to support different program demands. Evaluation will focus on the number of configurations possible. The larger the number of configurations (to a certain point[56]), the greater the number and types of uses that can be supported in the contained space.
2. Flexibility: Flexibility refers to the changeability of the system beyond the prescribed programs. In other words, this is a measure of whether this kinetic system can create configurations and spaces that are not yet known at the construction of this new building-edge. The evaluation of this characteristic essentially assesses the ease with which the system creates non-predetermined arrangements.
3. Reconfiguration Ease: The ease of set up and use is determined by how this system is rearranged. For example, the rearrangement of the system can be achieved through people pushing or pulling the elements around the space, or the reconfiguration can be motor actuated with a computer directing each element. Each method of moving the system elements has advantages and disadvantages, but this criterion is directed towards measuring how easily each piece of the system arrives in its new positions, and how much effort must be expended by the user to achieve the configurations.
4. Speed: Speed measures the length of time required for the system to change from one configuration to another. This is an important characteristic as it influences the potential frequency of configuration changes. The faster the process, the greater the amount of time that the space can be used for activities and the greater the number of feasible changes within a span of time. This characteristic can be evaluated through an understanding of the movement mechanisms and actuators.
5. User Characteristics: The user characteristics refer to who is capable of initiating or driving the reconfiguration of the system. These characteristics may include an age range, a particular skill-level, or an affiliation with the museum. Evaluation will identify the specific user characteristics for the system to assess the potential pool of users of the rearrangeable system.

[56] There is likely a threshold at which additional configurations no longer contribute to the usefulness of the space, or in other words, the new configurations offer no additional advantage for supporting a wider range of activities.

The five characteristics listed above outline the aspects that determine the ease of use and deployment for this rearrangeable system and how each attribute will be used for evaluation.

4.3 Summary for Evaluation

To ensure a transparent evaluation process for each design, the performance specifications created in the previous three sections is consolidated into a summary table. This table can be treated similarly to a checklist, but instead of checking for the presence of absence of each element, ratings can be provided to create a quantitative assessment of each design proposal. A "Ratings" column will replace the "Relevance" column later in this thesis when this table is used for rating. Currently, the "Relevance" column identifies each specification with the portion of the thesis for which the specification is relevant. A more complete table is also included in Appendix F.

Table 1: Summary Table of Performance Specifications and Evaluation Criteria

Performance Specification	Measure of Success for Evaluation	Relevance
	ENVIRONMENTAL STANDARDS	
Exterior Standards		
1. Weather-Tightness	Does the exterior edge shield the interior from outdoor weather conditions? Provide shelter for visitors and protect exhibit materials?	Mechanical Design: Materials Selection
2. Security	Does the exterior edge have strongly fixed kinetic elements to secure the museum's valuables? Is the material sufficiently impenetrable?	Mechanical Design
3. Corrosion Resistance	Is the exterior material corrosion resistant?	Materials Selection
4. UV Radiation Resistance	Is the exterior material UV radiation resistant?	Materials Selection
5. Non-flammability	Is the exterior material non-flammable to prevent the spread of an outside fire into the museum?	Materials Selection
Interior Standards		
1. Lighting	Can light pass through the walls? Can each area of the space be lit at all times?	Mechanical Design
2. Provision of Shade	Does the interior space provide refuge from direct sunlight?	Architectural Design
3. Air Conditioning	Does the interior/exterior edge have sufficient air-tightness for cooling and heating interior space with air-conditioning?	Mechanical Design
4. Electricity	Does this setup provide room for electric wiring to power the automated reconfiguration of the space?	Mechanical Design
	USAGE	
1. Programmability	How many distinct configurations are possible?	Architectural Design
2. Flexibility	Can this system create configurations outside the pre-determined and pre-set configurations?	Mechanical / Architectural Design
3. Reconfiguration Ease	How easily is this system set up and rearranged? Is the system computer-controlled? Motor-actuated?	Mechanical Design
4. Speed	How much time is necessary for the system to reconfigure? Is	Mechanical

	the time long?	Design
5. User Characteristics	Who is capable of reconfiguring this system? Does it require training or can anyone adjust the building-edge configuration?	Mechanical Design

The relevant specifications will be extracted for each category of design to create tables for evaluating each design. The architectural design process will provide a collection of potential building-edge systems; this table will serve as a systematic and quantitative means of rating and assessing each design and ultimately, selecting the most promising design. For the mechanical design, this table will function as more of a checklist for refining the mechanisms and selecting the materials.

5. Architectural Design

The result of the architectural design process was a form that this reprogrammable system ought to take, or in other words, the architectural design process has articulated the spaces that can be created and the type of armature necessary to create those spaces. Through an exploration of potential articulations of the performance specifications, a series of potential forms was generated. These forms were evaluated against the performance specifications and against the mechanical construction limitations using the table above. The evaluations of proposed designs are included in Appendix G.

This section will also provide a brief sample of how the architectural design has already begun to account for mechanical feasibility during the design process. The sample design process focuses on one of the three potential architectural designs explored by the planning thesis. This following section demonstrates the use of mechanical design in the architectural design process.

5.1 Flexible Armature

These forms seek to bring together the variety of arrangements that have already been presented, exploring the possibilities of having several of the proposals within the same system. The capability to realize more than one proposed form may lead to a system with greater flexibility and potential configurations that originally intended. Flexible armature refers to the elements that may remain fixed in the other designs, but in this design, would be rearrangeable as well. Thus, rather than focusing on specific configurations that have already been defined, this section outlines several design proposals focusing on how the flexible armature will move and how partitioning materials will be deployed. For each of these designs, the assumption is that each column can move to any point in the building-edge space.

1. Armature moves horizontally, Material deploys horizontally

The first of these models focuses on a single column as the starting point for all walls to deploy from (Figure 8). The deployed material can be coplanar in two directions or in completely different directions to create configurations such as the Sierpinski Gasket and the Dragon Curve.

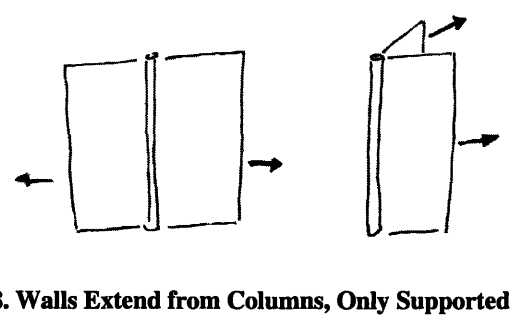


Figure 8. Walls Extend from Columns, Only Supported by Column

With the deployed material extending from a single column, the extending must be supported and deployed using some sort of a mechanism. The following figure provides a potential solution for deployment to confirm that this model warrants consideration and further exploration (Figure 9).

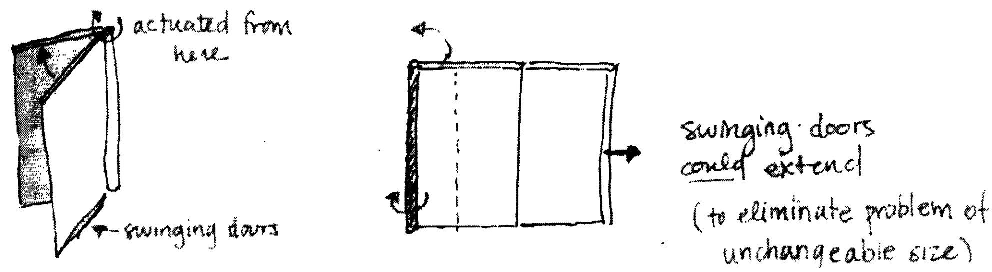


Figure 9. Single Column Rotation and Extension Methods

The rotation can be actuated from the post and material can be deployed using supports at the top of the material. This deploying material also eliminates the problem of walls with a fixed size, a problem with the swinging doors. The following figure reiterates this rotation and extension, but uses a second column to add further stability while also limiting the deployment of material to a single direction between the two (Figure 10).

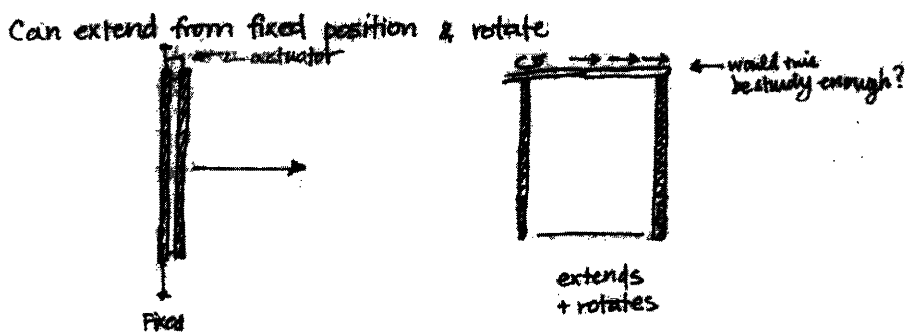


Figure 10. Double Column Extension Method

Another consideration with the first design that uses a single column that is raised by the previous figure is the need to have a sufficiently robust deployment mechanism to support the material that is deployed.

Building on the last two examples with a material deployed between two columns and material deployed in multiple directions, this final method of horizontal deployment from movable posts uses a cluster of three columns (Figure 11).

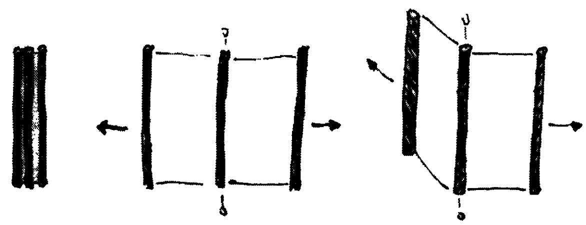


Figure 11. Three-Column Clusters with Fabric Deployed Between Columns

The struggle with this final method of deployment is the size that a cluster of three columns is heavier and bulkier, potentially increasing the difficulty of the reconfiguration process.

2. Armature lifts out of space, Material may deploy from subsequent orientation

Another way for the armature to reconfigure is through vertical movements. Vertical movements allow the armature to completely lift out of the space to completely clear the floor to create a truly open and uninterrupted space. This complete clearing is a characteristic unique to this category of flexible armature. The following figure provides a summary of the three potential ways that armature can lift out of the space (Figure 12).

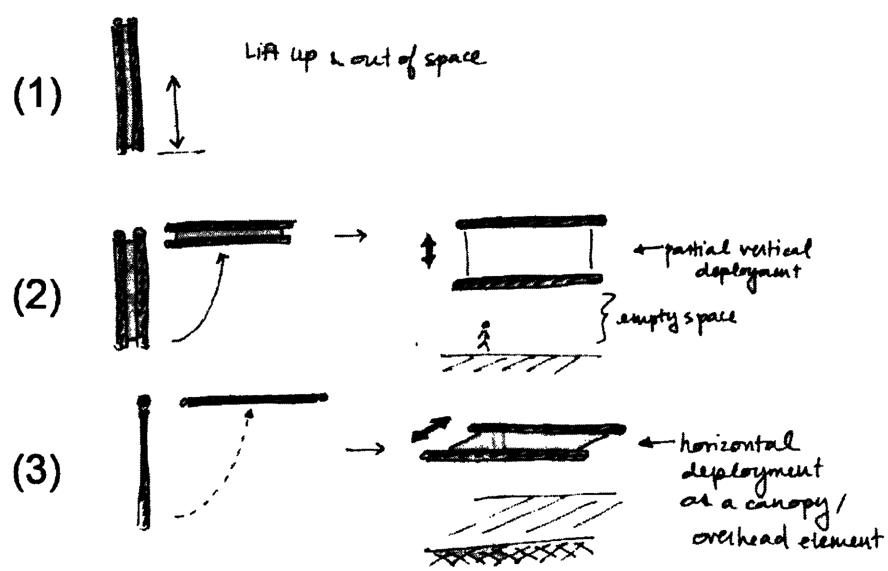


Figure 12. Three Potential Methods of Lifting Columns out of Space: 1. Straight Up, 2. Rotate Up with Vertical Deployment, 3. Rotate Up with Horizontal Deployment

Each of these lifting methods creates a partitioning element through the deployment of material between two columns; material is deployed when the columns are pulled apart. In addition, these methods also include a horizontally deploying capability as shown in the "Double Column Extension Method."

The first method lifts the armature directly out of the space without changing orientation. The advantage of this method will become more apparent through subsequent discussion on the disadvantages of the remaining two methods. The drawback with this design is the space needed to store these columns once they have been withdrawn upwards; this space will need to be as tall as the space below to completely remove the columns thus creating an storage space above with little flexibility and usefulness.

For the second and third methods, the armature is extracted from the space by rotating the armature upwards. The exact direction of the rotation differentiates the second design from the third. In the second design, one column ends below the other allowing for vertical deployment of material much like a window shade (Figure 13).

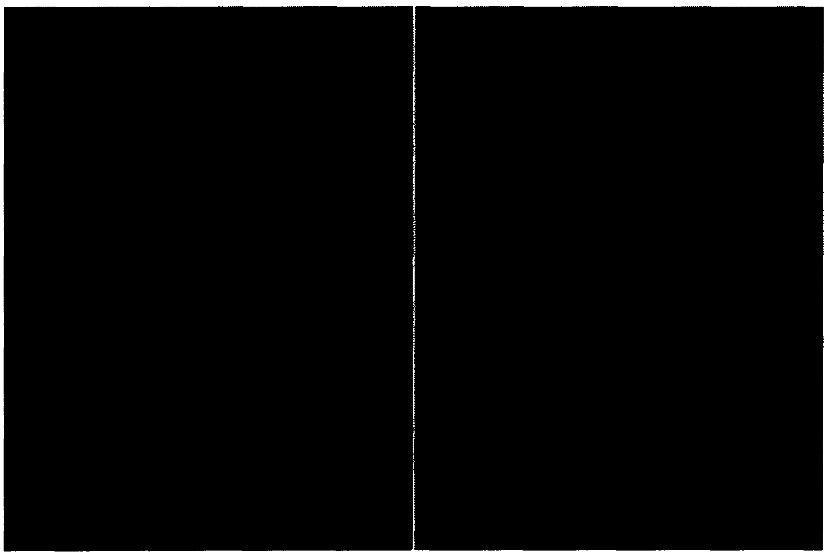


Figure 13. Example: Vertically Deploying Window Shade

In the third design, the pair of columns is rotated to the side and so that the columns end up side by side. When the columns are separated and the material is deployed, the material forms a horizontal plane to create a canopy or ceiling. This horizontal deployment creates a form not discussed in the performance specifications. Although not mentioned earlier, this design may allow this reprogrammable building edge to extend beyond the defined limits if the columns can extend out of the space to essentially create an awning. An awning provides a partially shaded or sheltered space for outdoor activities and sitting spaces.

5.2 Design Evaluation

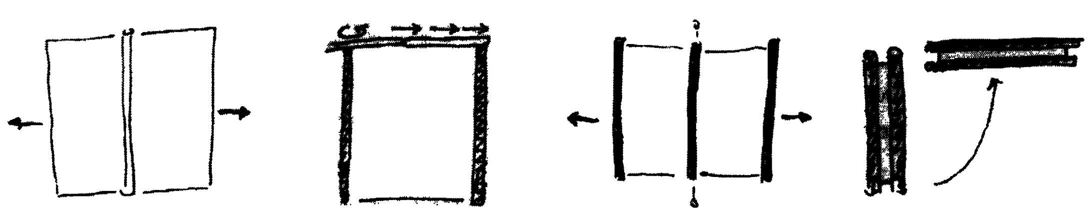
To evaluate each design proposal, the design concept was first assessed as a whole with some reference to the relative strengths and weakness of the other designs. Then, each design that still merited consideration was assessed against the relevant performance specifications. Through this process, the most promising architectural design emerged for further exploration and detailing and a subsequent mechanical design process. This section gives a brief evaluation of the most promising architectural design and the subsequent section discusses the evaluation of that design. Inherent in its conceptual design, a system with flexible armature naturally increases the flexibility of a space over its stationary counterparts. This proposal is really a proposal to build a system that can achieve other models that are based on straight edge walls. Any of the configurations possible with the relevant designs will also be possible with this system. This characteristic alone is sufficient to justify proceeding to the next stage of design.

5.3 Most Promising Design

Through the evaluation process, the planning thesis has determined that the most promising design is the system of flexible armature comprised of columns and deployable material. A general framework of function was defined in greater detail before proceeding to the mechanical design. This framework included how the columns will function, how they will be clustered, and the number of columns. The details of function will be elaborated in this section, while clustering and column count explanations are included in Appendix G.

Column function is dependent on how the material is deployed, retracted and stored. There were four potential solutions. The first solution involves a single column with material extending outward by some mechanism in one or two directions. The second solution uses a pair of columns with material stretched between them; the material stored within the columns is deployed as the columns are pulled away from one another. Similar to the prior solution, the third solution employs a cluster of three columns with two segments of material stretched between the three, or in other words, a center column with material deployed as the other two columns are pulled away. The final solution is also based on the second solution, but with an added hinge at the top to lift the columns out of the space to both clear the space and to allow vertical or horizontal deployment. The following table summarizes these column systems.

Table 2: Four Potential Column Systems for Wall Deployment



Extending Walls | **2-Column, Material Stretched Between** | **3-Column, 2-Direction Material Deployment** | **Hinged Columns**

To select a column system for further design, the feasibility and drawbacks of each of these column and material deployment designs are evaluated. As noted before, the largest concern of the extending wall system is whether the mechanisms for extending the wall can be strong enough. The 2-column design is promising as long as material deployment is actuated by the separation of the columns rather than an extending mechanism as noted in the diagram; using the columns for deployment allows the system to be sturdier with two firmly fixed material holders. The 3-column design is similar to the 2-column design and is equally as promising; the only drawback is the increased number of columns that may increase the density of columns and size of column systems resulting in crowding of the building-edge space. Finally, the hinged column is based on the promising 2-column design, but the hinging action is difficult to achieve cleanly; the following diagram demonstrates the obstacles for a hinged system (Figure 14).

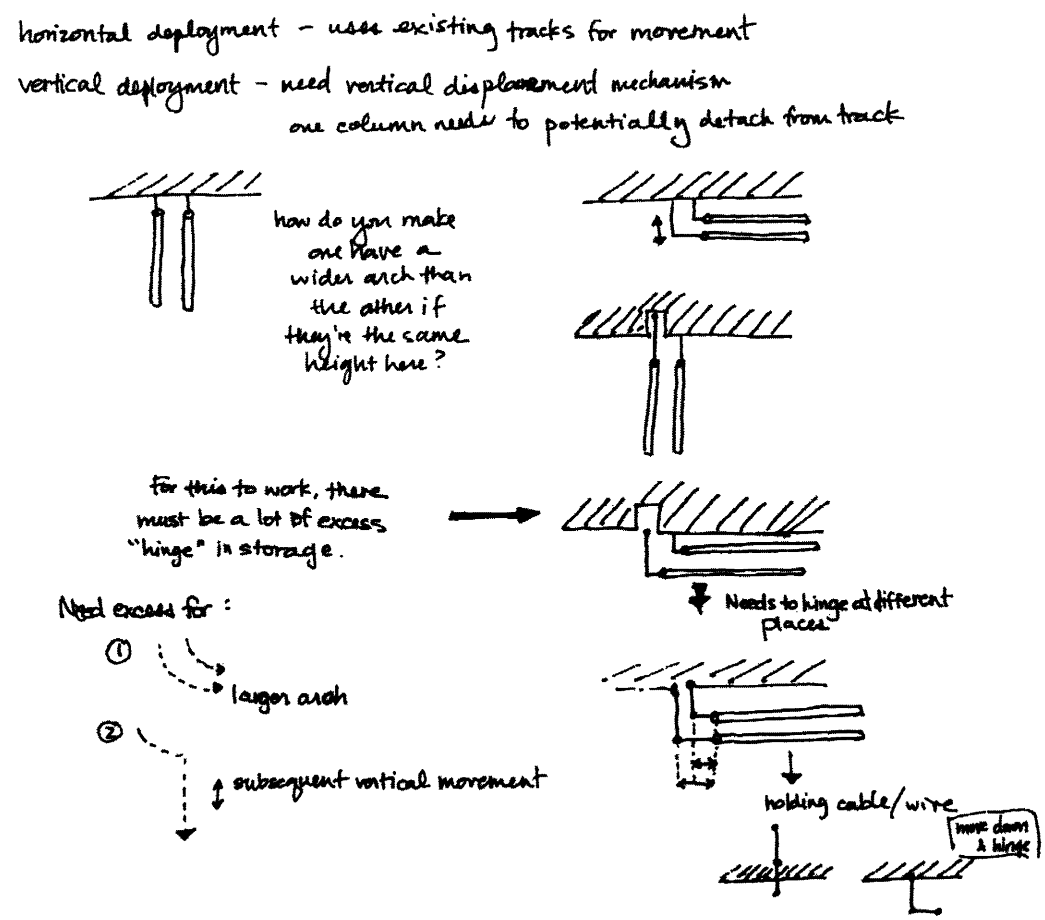


Figure 14. Obstacles in Design Exploration for Hinged Column Material Deployment

These diagrams illustrate the design process through which the hinged column was eliminated from consideration. The design evolved through consideration of the functional requirements of a hinged pair of columns. Horizontal deployment was determined feasible using an existing track system, but horizontal deployment where tracks already exist will for the most part deploy material below a ceiling, a pointless effort. Exploration of vertical deployment revealed the complexity of mechanical design necessary for realizing this concept. Consequently, this investigation confirmed that the hinged column would be unsuitable and that a 2-column material deployment system would best serve this building-edge system.

6. Mechanical Design

The mechanical design of this system yields the mechanisms and materials needed to construct and rearrange the movable elements of the most promising design that resulted from the architectural design process. To do so, the design is broken down into three stages: the basic framework of elements necessary for movement, mechanisms needed to achieve movement, and materials for construction.

The movement framework establishes the characteristics and elements necessary in this system based on the performance specifications and architectural design. This framework will provide general characteristics for the system as a whole. In addition, given the best design calls for moving columns, defining the groups of mechanisms to be designed to achieve movement is also important. The essential elements for movement include the column itself, mechanisms that move the columns both above and below, the tracks on which the columns will move, how movement is actuated (whether by electricity or by man-power), and in an automated system, how each column knows where to go.

Two additional considerations that may affect the mechanical design are weight and actuation. As a kinetic system, lightweight components will affect the ease, speed and feasibility of reconfiguration, three characteristics that are defined by the performance specifications. The mechanical design should also account for a possibility of computer control and actuation to minimize the expertise and human effort and energy necessary to reprogram the building-edge space.

6.1 Mechanisms for Movement

This section will include the functional requirements of the system and how each is met through the mechanisms, or in other words, the mechanisms to achieve movement will be defined. Also included will be the design process and calculations, and the considerations that were dealt with in each design.

6.1.1 Column and Deployed Material

For the columns of this system, there are two potential designs, of which the latter has already been selected earlier in this thesis and will be discussed in greater detail. The first design is mentioned again to further justify the selection of the second design. The first design uses a concept similar to vertical blinds where an initial piece pulls apart a series of blinds that have been strung together, forming a solid visual barrier. The material that is deployed is in small segments with an extending arm on top. As the arm extends, it brings material with it, creating a wall extended from the column. For the second design, each column will be a hollowed cylinder with material coiled inside. The material will deploy in a manner similar to a projector screen; the material can be pulled out easily, but there is also some retraction mechanism to recoil the material. Compared to the first design, this second method of deploying material is less prone to failure with fewer parts to breakdown or tangle. In addition, this second design is passive and does not require some sort of actuator to deploy the material. Consequently, the second design will

The first of the following figures shows a potential representation of the column and deploying material (Figure 15). The second figure demonstrates how material is drawn out. A single piece of the fabric is wound around two separate cores and inserted into two separate columns. The fabric is drawn out when the columns are pulled apart (Figure 16). Two rotational springs, one at the top and one at the bottom, are attached to the core to draw the material back when the columns are brought back together. Two rotational springs are needed to pull the material back evenly at the top and bottom.

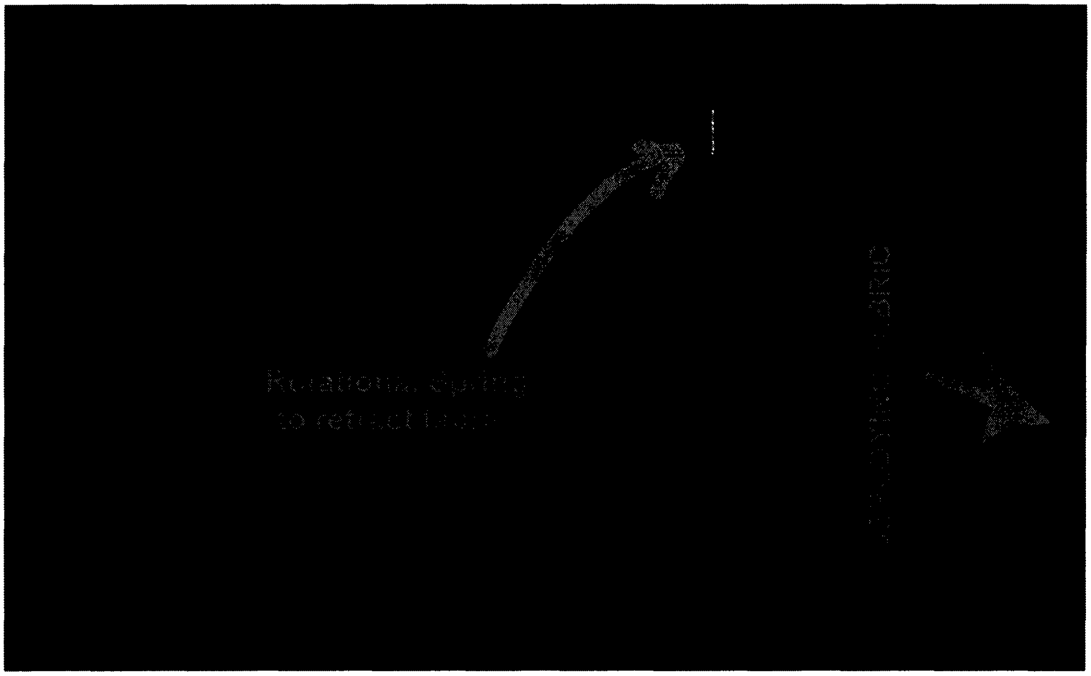


Figure 15. Column with Exploded View, Rotational Spring Noted

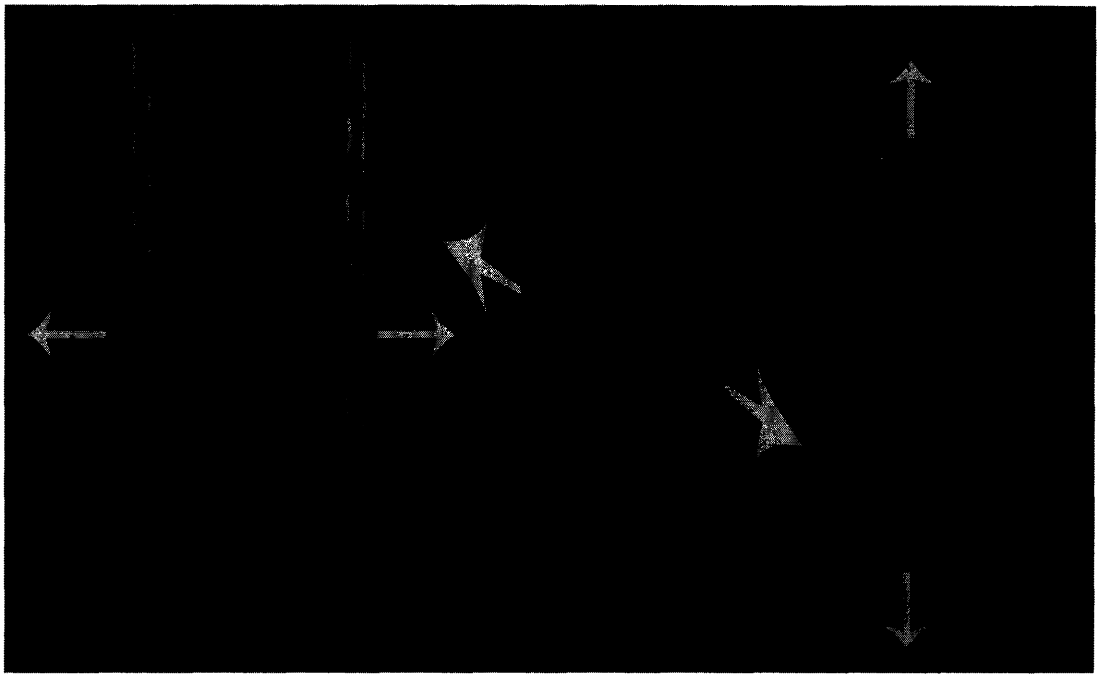


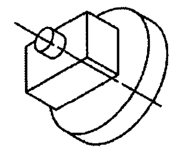
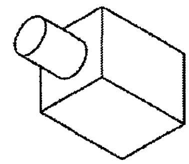
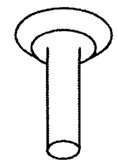
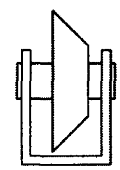
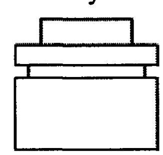
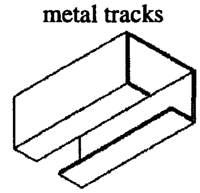
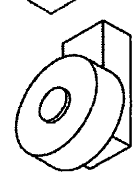
Figure 16. Deploying Material Between Pair of Columns

6.1.2 Movement Mechanisms Above Column

The system of movement mechanisms above the column is the most complex as this system must include the movement mechanisms for lateral movement as well as rotational movement of the column. In addition, the system must suspend the column, actuate movement and provide movement directions to the column. This section will first provide an overview of the parts and assembly. Then, the following discussion will document the mechanism selection process.

The following table provides an overview of the mechanisms that need to be specified for the system of mechanisms above the column.

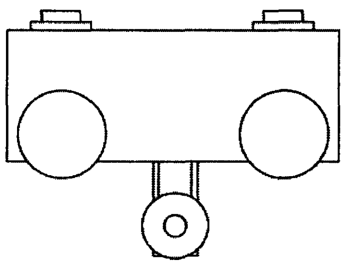
Table 3: Overview Table of Movement Mechanisms Above Column[57]

Purpose	Mechanism (Number Needed)	Supporting Parts	Diagram
1. Lateral Movement	Wheel (4)	Bearing, Axle	
2. Actuate Lateral Movement	Motor (2)	Belt	
3. Rotational Movement	Beveled Gear (1)		
4. Suspend Column	Pair of Beveled Gears (2)	Bearings, Axles	
5. Find Position	Sensor (1)	Counterpart to provide sensor location information	Placed above entire housing with counterpart inside the track system.
6. Fix Column in Position	Electromagnet (2)	Holes in bearing system for insertion	
7. Receive Directions/Send Status	Radio Frequency (1) Transmitter/Receiver	Encased in non-conducting material	Placed on/near stabilizing wheels to remain on outside of metal tracks
8. Contain Parts	Housing (1)		
9. Stabilize System	Stabilizing Wheels (2)	Axle, Spring-Loaded Extension	

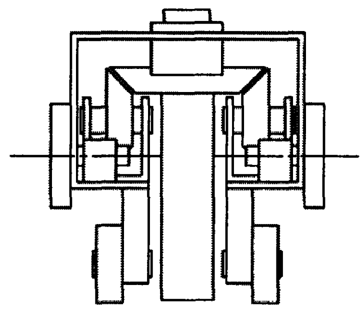
[57] See Appendix A for detailed drawings with dimensions.

When all these parts are assembled, the system will appear as the following table shows:

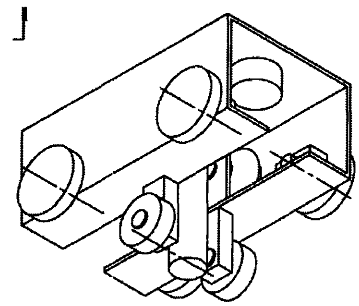
Table 4: Three Views of Assembled Mechanisms, Above Column[58]



Side View



Cross-Sectional View



Upward Isometric View

Through the preceding nine mechanisms and their supporting parts, the assembly above can be created and used to move and deploy the walls of this rearrangeable system. The bare minimum parts were wheels for movement and a mechanism to carry the column while still allowing free rotation. The remaining parts were added so that the system would be more stable, controlled and precise. The following list discusses the mechanism selection process in greater detail for each function.

1. *Lateral Movement:*

   The obvious mechanisms for this purpose are wheels which can be attached to the exterior of the system to run along the tracks. The two supporting components are the wheel's axle and a bearing block to support the axle. The axle needs to extend from the outside edge of the wheel, through the housing and protrude out of the bearing block (Figure 17). The bearing block can be constructed from a box extrusion to provide two supports. This wheel support system will allow the wheel to freely rotate while preventing twisting of the axle, thus stabilizing the wheels. Four wheels will be ideal for suspending the entire system in the track system and for maintaining stability to avoid tipping forwards and backwards.

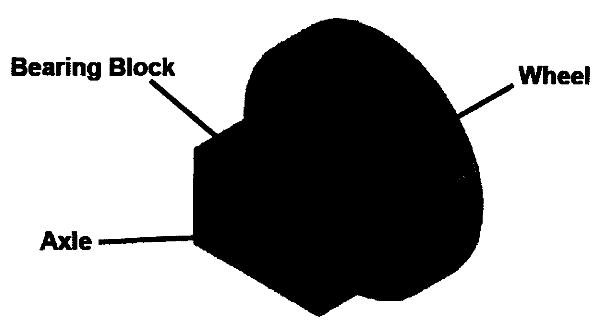


Figure 17. Wheel, Bearings, & Axle Setup

[58] See Appendix A for dimensioned drawings.

2. Actuate Lateral Movement:

A motor will be used to actuate the movement of the wheels. The motor drives the shaft through a belt that circles the shaft of the motor and the wheel axle, transferring motor shaft rotation to axle rotation. This system only needs two driven wheels as back-wheel-drive or front-wheel-drive, depending on the direction of movement, is sufficient to move the entire system.

A gear train was also considered as it provides the potential for greater precision but was ruled out because of higher maintenance costs and risks. Gears and belts will both wear, but gears offer less give. The elasticity of a belt allows the belt to absorb shock or overextension without significant damage. In contrast, when under sudden stress, gears have the risk of teeth shearing off. In addition, the cost of replacing a belt is cheaper as a belt fewer parts and is less complex. In order to replace a gear train, parts of the assembly must be disassembled between the motor and wheel and their supporting components. While belts may wear more quickly and require more frequent replacement, the added complexity of replacing worn gears adds significantly to the cost of maintenance.

3. Rotational Movement:

Rotational movement will be a passive movement, driven by the separation of columns during the rearrangement process. Consequently, the design for rotational movement has one requirement: free rotation for the column. Linked to the next part, rotational movement of the column is allowed by a beveled gear that is directly attached to the column, creating the only point where the column is connected to the mechanism system above. The presence of a system of beveled gears to suspend the system permits the column to rotate freely as there are no other contact points for the column for the column to grind against the track or housing.

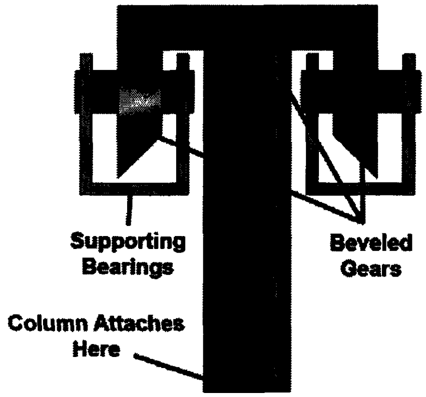
An additional mechanism, although unnecessary, is a cylindrical sleeve that is secured to the housing to further stabilize the column. Within the sleeve will be ball bearings for the contact between sleeve and column to maintain free rotation.

4. Suspend Column:

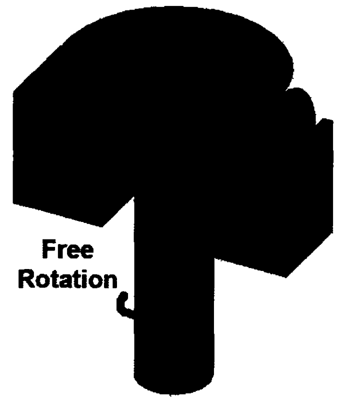
Rotational movement and column suspension were each designed with the other in mind. Consequently, the two mechanisms are interrelated: the beveled gear for rotational movement is suspended by two beveled gears on either side of the system to allow the free rotation of the column while supporting the column from within the system. The advantage of this beveled system is that it reduces the need for the column to hang onto any part of the housing system which may cause friction and wear each time the column rotates.

Other ideas had included simply creating a hold in the housing for the column and placing a large ball bearing at the top of the column. While this succeeds in suspending the column, the ball bearing gives the column too many degrees of freedom for movement (the column should not be able to flip up) and has the problem of friction and wear.

Table 5: Column Suspension System



Front View, Parts Labeled



Isometric View, Rotation Noted

5. Find Position:

For this rearrangeable system, the complexity of configurations and movements to arrive at those arrangements requires that each micro-system of column and mechanisms know where it is going and if it has arrived there yet. For each system to identify a specific location in the virtual grid and to know its spatial status, each micro-system needs a sensor that can read the grid that is laid out in tracks. This may be an interaction between a sensor on the micro-system and the system of sensors arranged in the tracks. A sensor itself would be placed on the track system with the sensor's counterpart or trigger on top of the housing of the carriage. As the carriage moves through the tracks, the trigger signals the sensors in the tracks of its location. With a feedback system, the sensor could alert the system of the carriage location and then return movement directions through the receiver/transmitter system.

6. Fix Column Position:

In order for the columns to remain fixed in place once they have arrived at the correct location, a mechanism is needed to stabilize the system and attach the mobile parts to an immobile component. This component, an electromagnet, is particularly important to maintaining the organization and structure of the changing configurations. The ability of the column to remain solidly fixed ensures that walls do not move accidentally or give way when bumped or pushed.

The electromagnet achieves this function as its name implies – a metal element is deployed and retracted through the presence and absence of electric current. An electromagnet is a temporary magnet comprised of a metal core within a wire coil. When current flows through the coil, a magnetic field is created within the wire coil and the core is magnetized; polarity is determined by the direction of current while strength is determined by the number of coils.[59]

[59] Museum, Canada Science and Technology. (2006). "Background Information for Magnets." Retrieved 20 April, 2006, from http://www.sciencetech.technomuses.ca/English/schoolzone/Info_Magnets.cfm.

For the purpose of locking the column in place, a pin should be deployed upwards to secure the top of the column. There are two states of the pin: up and down. To determine which setting corresponds with the non-magnetic state of the electromagnet, a power outage situation was considered; in the case of no electricity and thus no current flow, for the sake of safety, the column ought to remain securely positioned. Consequently, the electromagnet pin will remain up when there is no current and will be pulled down by magnetism when current is applied. This can be achieved through a mechanical spring that pushes the pin upwards into a cavity on the track system until a magnet below overcomes the spring force, thus unlatching the column for travel around the building-edge space.

7. Receive Directions/Send Status:

In order for the entire module to move about the defined space, the module needs to be able to receive directions for how to move and to send information about its status so that the central computing system can direct subsequent and future movement. Because of the potential complexity of movements, these transmissions should we wireless transmissions. Given the bounded range of transmission, a radio frequency similar to that of a cordless telephone will be sufficient for information transfer between the central control system and each column module. Other common examples include garage door openers and baby monitors.

The following figure is a flow chart of how the base unit of a cordless telephone functions (Figure 18). Note the transmitter/receiver and antenna, two components that will be necessary for data transmission to the motors in the module above the column. The power components will also be needed, and the battery charger will be replaced by electrical wiring.

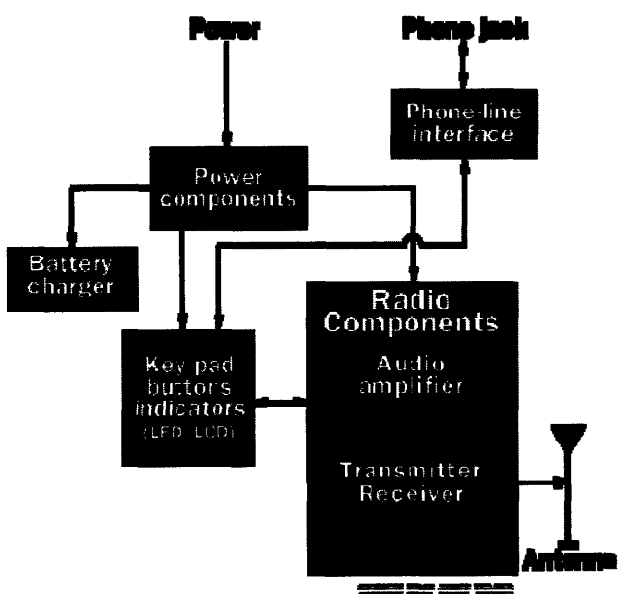


Figure 18. Base Unit Block Diagram[60]

[60] Freudenrich, Craig C. (2000). How Cordless Telephones Work. cordless-telephone-diagram-handset.gif, HowStuffWorks. 340 x 293.

The next figure is a flow chart diagram of the handset unit (Figure 19). Again, note the transmitter/receiver and antenna. The keypad buttons indicators are also relevant; for precision in movements, sensors will be needed to mark specific locations in the system which will interact sensors on the column modules to confirm column placement.

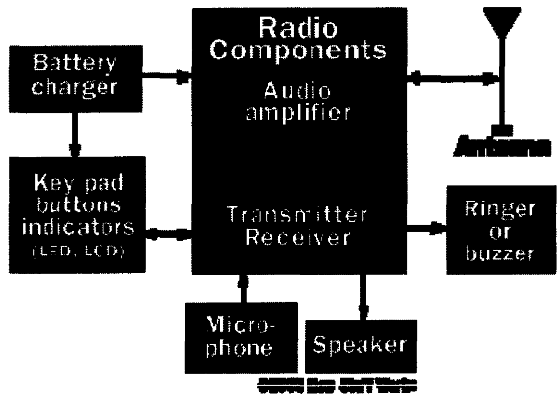


Figure 19. Handset Unit Block Diagram[61]

The transmitter and receiver send information through FM radio frequencies. The transmitter on the handset and the receiver on the base operate on one frequency while the receiver on the handset and the transmitter on the base operate on another frequency; this maintains the separation of information flow. For example, the General Electric cordless phone from 1993 operated on two frequencies: 44.32 MHz and 49.28 MHz (Base: 44.32 transmitter, 49.28 receiver; Handset: 49.28 transmitter, 44.32 receiver).[62] The following table shows the frequencies that have been approved for use by the Federal Communications Commission.[63]

Table 6: FCC Approved Frequency Bands for Cordless Phones

Frequency Bands	# of Channels	Approximate Range
45 – 50 MHz	10 – 25	1000 ft / 330 m
900 MHz (900 - 928 MHz)	20 – 60	5000 – 7000 ft / 1500 – 2100 m
2.4 GHz **5.8 GHz**	50 – 100	> 5000 – 7000 ft

According to this table, the ideal frequency band that this system will use to transmit information will be the 2.4GHz or 5.8 GHz bands. All of the bands have sufficient range as this system is 100 feet at its widest point and under 109

[61] Freudenrich, Craig C. (2000). How Cordless Telephones Work. cordless-telephone-diagram-base.gif, HowStuffWorks. **384 x 416.**

[62] Freudenrich, Craig C. (2000). "How Cordless Telephones Work." Retrieved 22 April, 2006, from http://electronics.howstuffworks.com/cordless-telephone.htm.

[63] While this reprogrammable system is for a park in Spain, this thesis assumes that the available frequencies in Spain are comparable.

feet along its longest diagonal of the three-dimensional space (Figure 20).[64] The 2.4 and 5.8 GHz bands are selected because of the number of potential channels. Each column would need to operate on its own channel, and potentially each column may even need two channels – one to send and one to receive information. These systems would be more expensive than the other lower frequency systems, but the number of channels cannot be compromised as each column must be able to send and receive information independently to move independently.

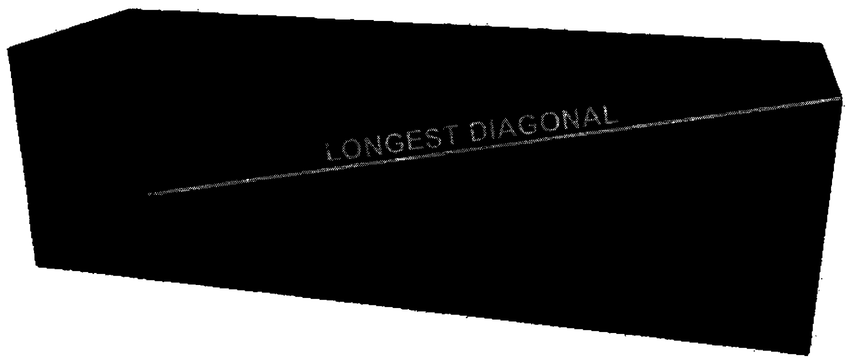


Figure 20. Context Model with Longest Diagonal Marked

The final consideration for the receiver/transmitter is related to its placement: the receiver/transmitter must be outside of the housing and track system because the transmission of radio signals is blocked by conducting materials. For the sake of strength and durability, the housing and track system will most likely be constructed of a metal. Consequently, this radio transmitter and receiver will need to be outside of both of these structures. The best location for the transmitter/receiver system is based on the overall construction; the stabilizing wheels are on the outside of the metal tracks and carriage thus providing a location for the transmitter/receiver.

8. Contain Parts:

With so many individual parts that must be a part of this column module, a shell or housing is needed to contain the different elements. This housing must support the wheels and column system as well as provide a place for the electromagnets to reside that allows them to lock into the bearings system. In addition, the housing must provide a location for the transmitter and receiver and their antennas.

The following figure shows a design for a metallic housing that essentially creates a car to hold all these parts (Figure 21). The transmitter and receiver will be placed above this housing in a small polymer casing. The transmitter and receiver cannot be held within this metal housing as conducting materials absorb

[64] This diagonal is calculated from treating the space as a rectangular prism and taking the diagonal from the top left back corner to the bottom right front corner.

radio transmissions. This housing will need to be able to hold substantial weight from the column and mechanisms.

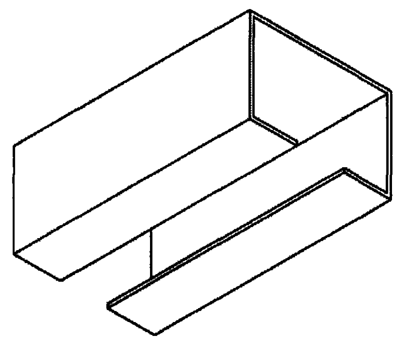


Figure 21. Metal Housing

9. Stabilize System:

   The final component of this system is a set of wheels that goes outside and below the housing. These wheels will stabilize the housing by helping the housing to remain in constant contact with the bearings. The wheels will be on springs with the springs pulling upward; these stabilizing wheels, in conjunction with the wheels within the housing which apply force through gravity, will essentially clamp the bearing. This clamping action will stabilize the housing to prevent any rocking in the tracks.

6.1.3 Track System

There are two potential designs for the track system along and on which the columns can be moved. To minimize the number of columns necessary and to achieve configurations that use the entire depth of the building-edge space such as the Sierpinski Gastket, the tracks need to allow movement along both the depth and width of the space. To achieve these two directions of movement, intersecting tracks are necessary. The first design involves a track that functions like a road; the track is a passive system on which the column turns itself. At each intersection when a column needs to change direction or move to another parallel track, the wheels on one side will rotate more than on the other to effectively turn the entire system. The second design involves bearings intersecting at a right angle. When a column has reached an intersection point, a section of the bearings rotate 90° to change the orientation of the column, and the column can continue moving as before.

The first track system, while it appears promising in plan, is difficult to design properly for a suspended column. In plan, the movement mechanisms for the column can be reduced to a small remote-controlled vehicle. With more rotation of the wheels on one side, the entire car can be turned right or left to follow another set of tracks. The difficulty arises when a column is suspended from the car, so a space must be left down the center of the track for the column. With a space down the middle, the track becomes more difficult for the car to follow as the car must turn around the corners without falling through the gaps. This consideration will require an analysis of wheel size and gap size.

The second track system is more easily and simply constructed. This track system can be designed independently of the system of movement mechanisms unlike the first track design. Here, the column and its mechanisms are the passive elements rather than the track system. In this design, an x-shaped piece of the track rotates at every juncture (Figure 22) after the column is centered in the x-shaped piece (Figure 23) and is ready to turn. To allow for smooth rotation and minimal loss of contact between the track and module running along the tracks, the rotating piece is cut as if it were a part of a circle (Figure 24).

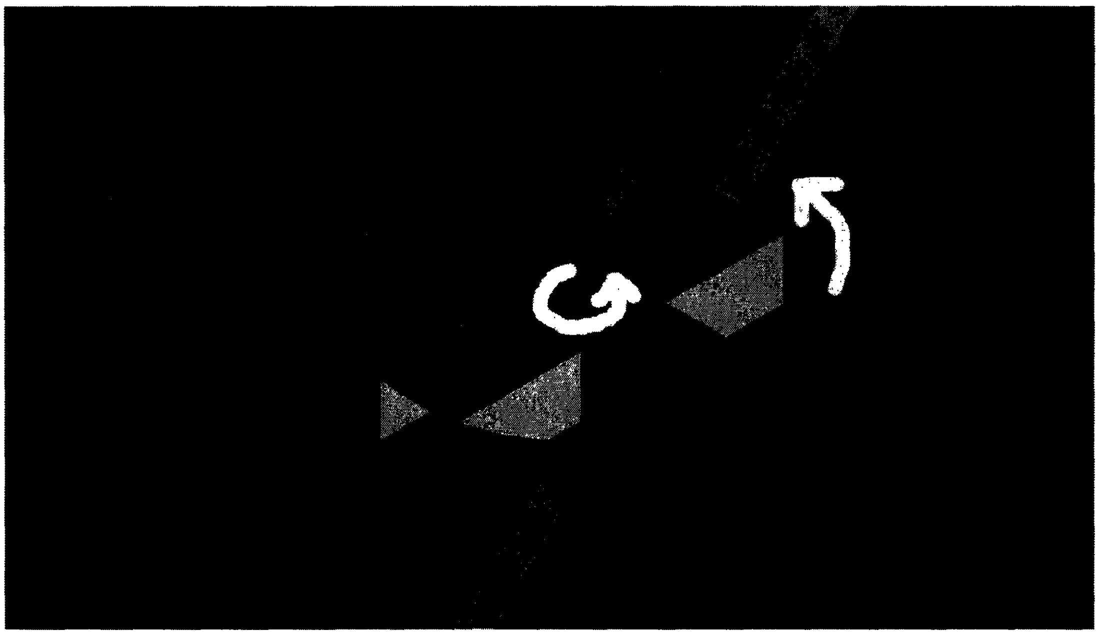


Figure 22. Rotating Track Component, Isometric View

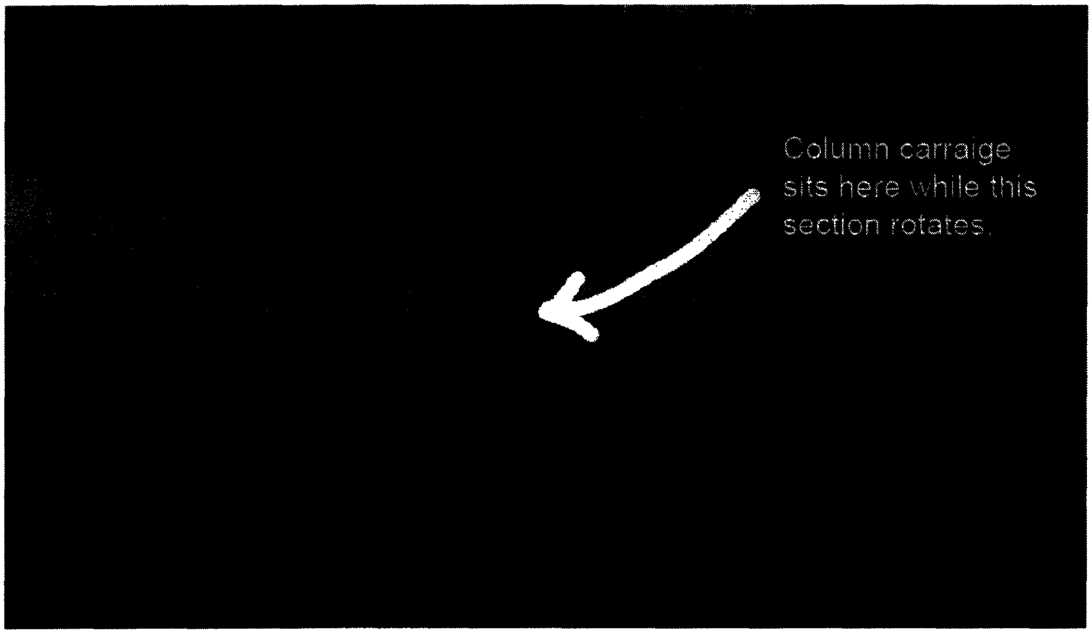


Figure 23. Underside of Rotating Track, Carriage Location Noted

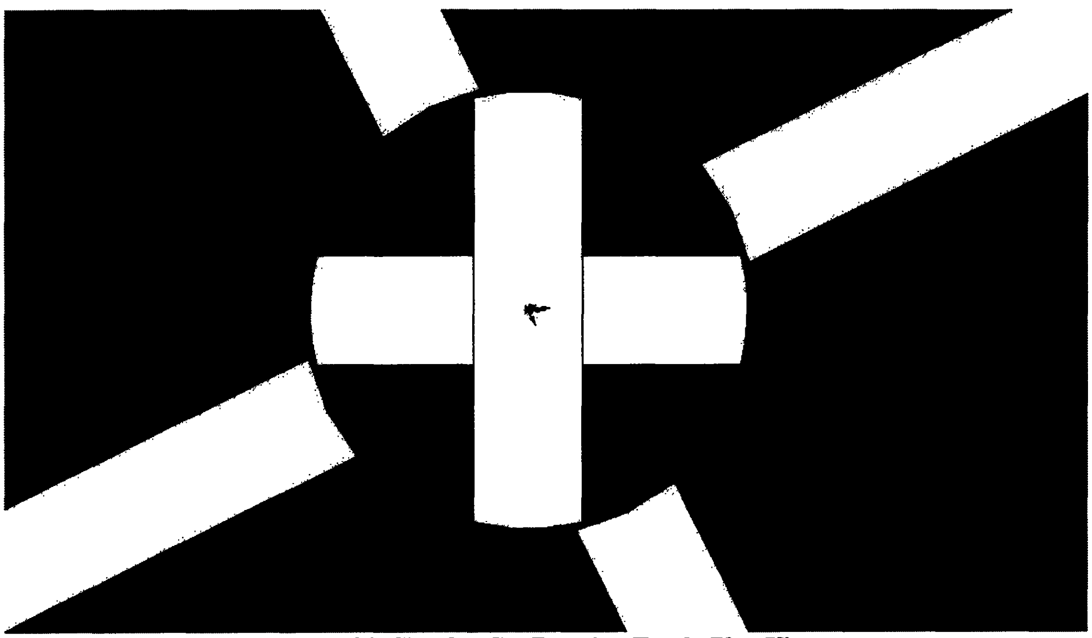


Figure 24. Circular Cut Rotating Track, Plan View

The mechanisms for rotating the x-shaped piece of track will be situated above the track. Mimicking the rotation mechanisms for the column, this rotation will be based on three beveled gears. In addition, the housing that will hold these rotational mechanisms is much like the carriage that houses the mechanisms for moving the column, as this housing also requires a gap for a post that extends downwards and two lips to support two other beveled gears. Unlike the column, the rotation of this piece of track is not passive; a motor is attached to one of the two vertically oriented gears to drive rotation once the column-carrying carriage is in place. The following figure shows the rotational mechanisms and housing (Figure 25).

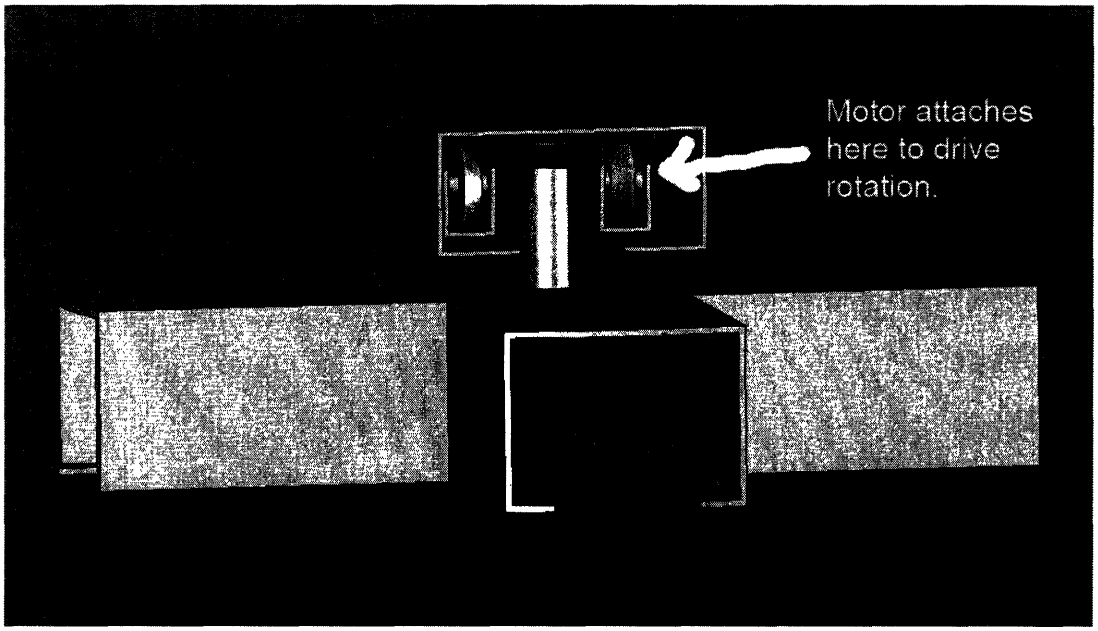


Figure 25. Track Rotational Mechanisms, Motor Location Noted

Because the ceiling of a building is rarely completely flat because of the imprecision of building construction, the bearings and the rotational mechanisms cannot be directly attached to the ceiling. Instead, the tracks need to be attached using black 5/8 inch black irons placed periodically along the length of the bearings. Black irons are thick rods that are threaded on one end and will be attached to the bearings on the other end. The threaded piece will be inserted in the ceiling; the threads allow rotation of the black iron to adjust the height of the bearing. Through adjustments of all the black irons, the bearings can be made to be perfectly horizontal. This precision will allow the column to travel more smoothly.

For the track design covering the entire building-edge space, five primary tracks for movement will run the length of the building front with three perpendicular tracks, two on either end and one in the middle. The following diagram demonstrates this setup (Figure 26).

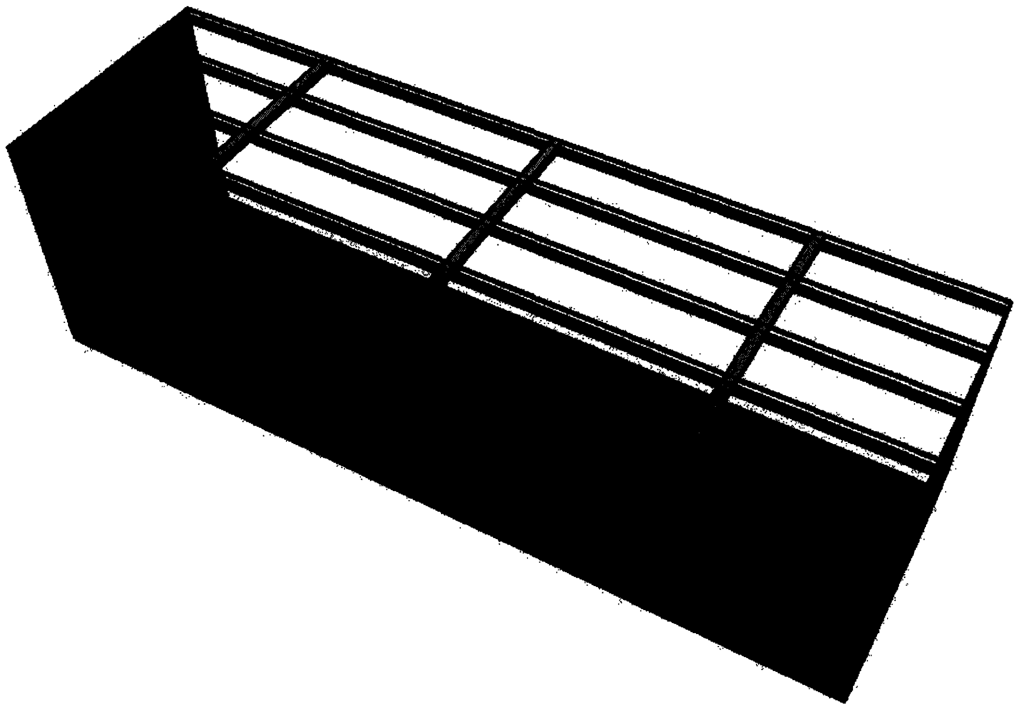


Figure 26. Track System, Isometric View

There are five primary tracks needed based upon the design of the Sierpinski Gasket; five are necessary to create the layers of triangles in the Sierpinski Gasket. The rationale for having three sets of perpendicular tracks is that too many will increase the complexity of movement and clutter the space above the columns, but three tracks would sufficiently minimize the distance that columns must travel to switch primary tracks.

The final element of this track system is related to the movement mechanism above the column: the track system needs holes punched into the material for the electromagnet pins to deploy into and thus fix the columns in place. These holes, the size of the electromagnet pins, will be placed in regular intervals down the length of every track. The number of holes determines the flexibility of column placement. Consequently, these two-hole clusters should be placed such that columns can be placed side-by-side, with their carriages just touching, down the length of the track.

6.1.4 Movement Mechanisms Below Column

The primary purpose of the mechanisms below the column is to further stabilize the column so that the column does not begin to tilt. Consequently, this is primarily a passive system. The necessary components include a part to allow lateral movement, the connection to the column, and a part to allow rotational movement. In addition, this section will discuss the ground track system for these mechanisms.

1. Track:

   The track below the column will have the identical layout as the track above, but the opening for the track will be much narrower. An open track along the ground poses a safety hazard for which shoes and feet can be caught and cause tripping and thus ought to be as narrow as possible while still serving its functional purpose. This will be less than an inch wide. Another reason for a narrow gap is that an opening in the floor naturally becomes a debris gathering place. Consequently, below this lower track a drainage system is needed that can be periodically flushed with water to clear the track of debris.

In addition to the narrow track, the lower track also needs the ability to rotate for the entire column to change directions. While the rotation of the track above and below will be difficult to perfectly sync without a direct connection between the two, the free rotational ability of the column will account for this. To achieve this rotation, the identical setup is used where the beveled gear attached to the column is supported by two other beveled gears, one driving and the other passive.

The gap in the floor is best protected through a flexible brush like covering that the column can easily push away while still easily returning to its original state. A common example of what this brush material will be like is a toothbrush – when used, the nylon bristles are deflected, but once the pressure is released, the bristles return to their original position (Figure 27).

Figure 27. Nylon Bristles on Toothbrush

2. Housing:

The lower module of mechanisms ought to have a housing similar to that of the upper module. This housing will be smaller as there are fewer mechanisms to contain, but again must provide a way to support the wheels and provide an opening for a connection to the column.

3. Wheels:

The wheels will be similar to the ones in the upper module; four wheels on axles, supported by bearings and placed on the sides of the housing. They will run along the tracks and be rotated in the tracks at junctures. As the housing and bearing system will be smaller than the ones above, the wheels will also be smaller in size.

4. Column Connection (includes rotational movement):

The connection between the column and this system need not be as strong as the connection above as this connection does not bear the weight of the column. Consequently, this connection, which is cylindrical rod, can be much smaller in diameter to fit within the 1 inch gap in the floor. To allow rotation, this connecting rod will be held in place using a cylindrical sleeve with ball bearings to contact the rod. This sleeve will then be welded to the housing.

6.2 Materials Selection

This section will discuss the functional requirements and performance specifications and the basis for the material selected for each mechanical and non-mechanical component. An important part of this process is the use of the Cambridge Engineering Selector. While some of the materials selected are based on precedents, an explanation of the Cambridge Engineering Selector will help clarify the program itself as contribute to an understanding of the materials selection process.

The following graphs and table provide a brief description of the elements of this program that are relevant to the materials selection process for this reprogrammable system. To select materials, the selector creates Ashby diagrams of the materials in its database and uses a color code to plot them by material type. The following graph is an example of an Ashby diagram by this program (Figure 28).

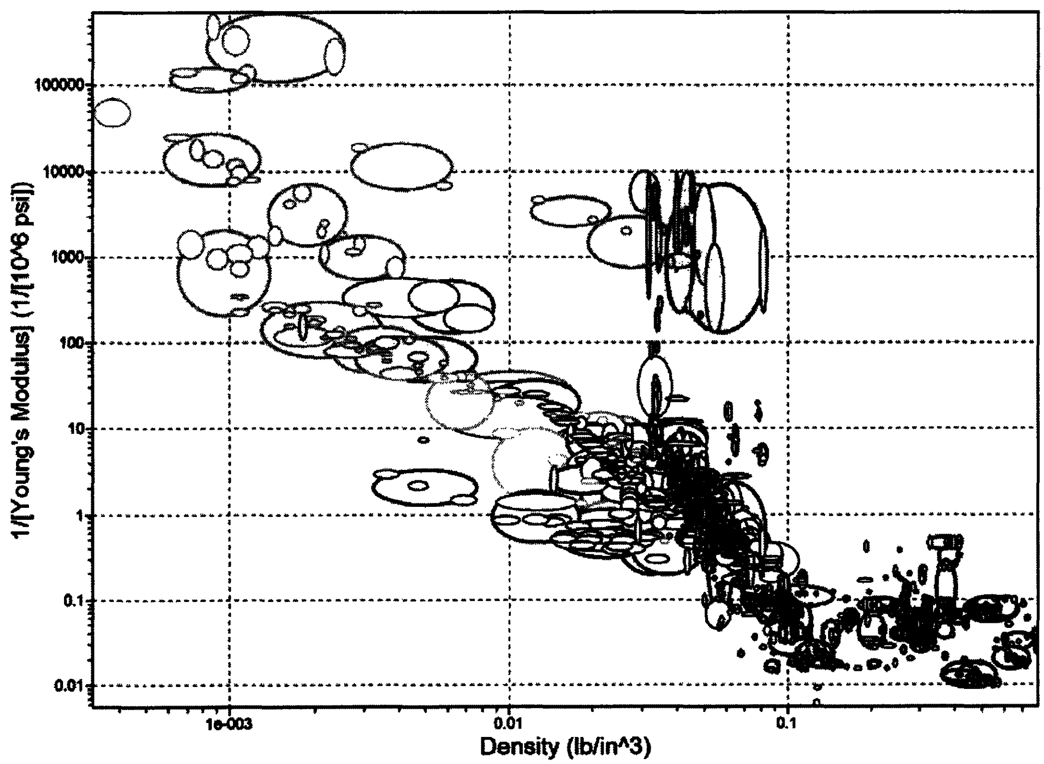


Figure 28. Typical Ashby Diagram[65]

When two material properties are selected in the Cambridge Engineering Selector, an Ashby graph is generated. Each circle in the diagram above represents a material in the selector's database and plots the range of the material in the two specified material

[65] Chai, Shutsu (2006). Typical Ashby Diagram. Cambridge Engineering Selector, Granta Design. Cambridge. 1579 x 1172.

properties. The following table provides a key for the color scheme and materials groupings.

Table 7: Material Groups Key

Material Group	Color
Ceramic	Pink
Composite	Maroon
Foam	Dark Blue, Bright Blue
Metal	Red, Purple
Natural	Green
Polymer (Polymer Foam)	Blue (Light Green)

The next graph describes the trade-off curve that is used to assess which materials best meet the criteria. The trade off curve is named as such because along this curve each desired property is traded for the other from one end to the other. In other words, the ideal states for each property are on opposite corners of the graph. Consequently the best material lies somewhere along the middle of the trade off curve where the material is not too dense or too heavy while still having a high stiffness, which is measured by the Young's Modulus (Figure 29).

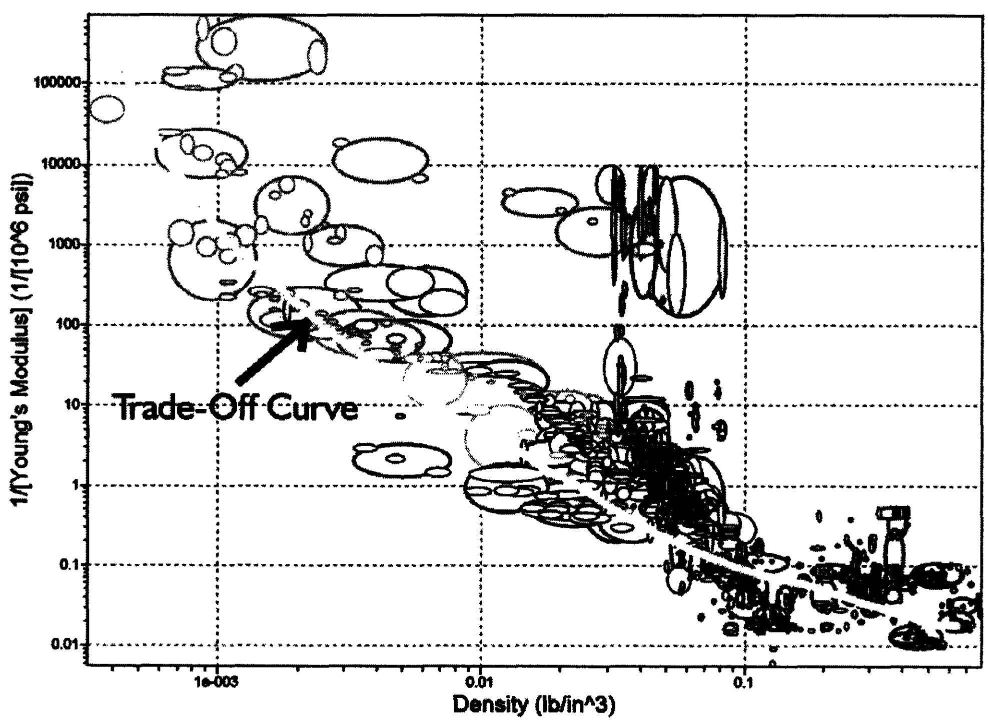


Figure 29. Trade-off curve between strength and weight[66]

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[66] Chai, Shutsu (2006). 1/Young's Modulus vs. Density with Trade-Off Curve. Cambridge Engineering Selector, Granta Design. Cambridge. **1579 x 1172**.

Demonstrating the earlier description of the trade-off curve, the metals are in the lower right-hand corner with the highest value of Young's Modulus indicating the highest stiffness, but also with the highest density, an undesirable characteristic. The upper left-hand corner has the lowest density and thus the lowest weight but also has the lowest stiffness.

Lastly, the materials selection process does not discuss a number of the mechanisms described in the previous section in name. The reason for this omission is that these remaining mechanisms will all be made of the same material: stainless steel. The last subsection will explain this reasoning and final selection process.

6.2.1 Wheels

The materials selection for the wheels of this system is based on the precedent of inline skates or rollerblades (Figure 30). Rollerblades are a suitable precedent as their wheels are of similar size, carry a comparable weight, and experience similar – if not significantly more – abrasion and wear. Consequently, like rollerblades, the wheels of this system should be made of polyurethane.

Figure 30. Roller-blades with Polyurethane Wheels[67]

Polyurethane is a material that wears well – under constant abrasion, the rate at which polyurethane wears down is relatively low. When materials are separated into five relative categories using the Cambridge Engineering Selector, polyurethane falls into the second best category, the "good" category.[68] The best category, the "very good" category is primarily comprised of metals, ceramics and composites, materials that are very hard and not conducive to rolling on a metal bearing.

6.2.2 Housing (for transmitter)

The housing for the transmitter must allow radio frequencies to pass through. Conductive materials such as metal and concrete are generally difficult for radio waves to

[67] Chai, Shutsu (2006). Roller-Blades. PowerShot S410 Digital Elph. roller-blades.jpg. Cambridge. **2272 x 1704:** Rollerblades with polyurethane wheels.

[68] Categories are: Very Good, Good, Average, Poor, Very Poor.

penetrate while ceramics have varying levels of conductivity. In contrast, polymers are generally non-conducting. Using the Cambridge Engineering selector, polyvinylchloride is selected for the housing of the transmitter. The following graphs present the graphs and materials distribution that led to this conclusion. Resistivity is the inverse measure of conductivity; resistivity measures the resistance of a material to current flow while conductivity is the ease of current flow through a material. For the housing around the transmitter, a higher resistivity is better for radio frequency penetration. An arbitrary threshold was set at 1×10^{15} near the upper limit of natural materials; this decision is based on the reasoning that most natural materials are penetrable by radio waves, so setting the threshold above this point will capture only those materials that are sufficiently resistive to current flow, or sufficiently permissive to radio waves.

The first graph displays this threshold on a graph that compares price to resistivity (Figure 31).

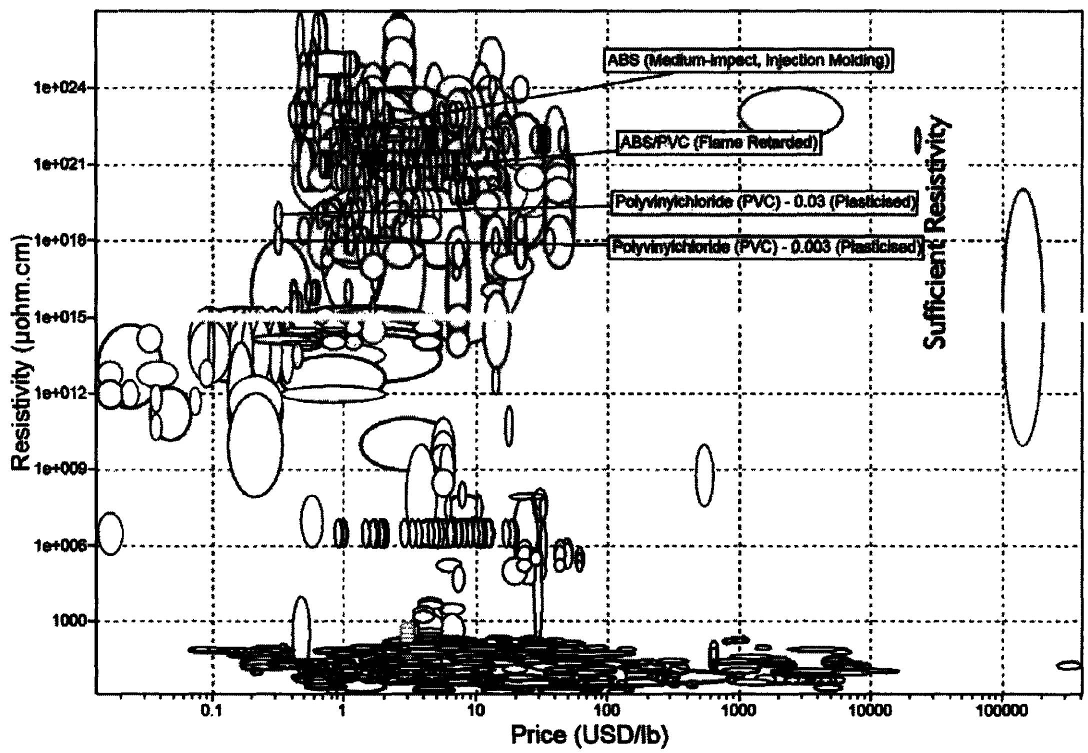

Figure 31. Resistivity vs. Price, 1×10^{15} Resistivity Threshold[69]

Polyvinylchloride (PVC) appears as one of the lowest cost polymers above the designated threshold. Acrylonitrile Butadiene Styrene (ABS) was selected as another common polymer material to test against PVC to ensure that PVC is the best choice. To further

[69] Chai, Shutsu (2006). Resistivity vs. Price, PVC & ABS Labeled. Cambridge Engineering Selector, Granta Design. price-resist-PVC-label.jpg. Cambridge. **1589 x 1165**.

test this conclusion, resistivity was plotted against density to see how PVC compares in weight to other available materials (Figure 32).

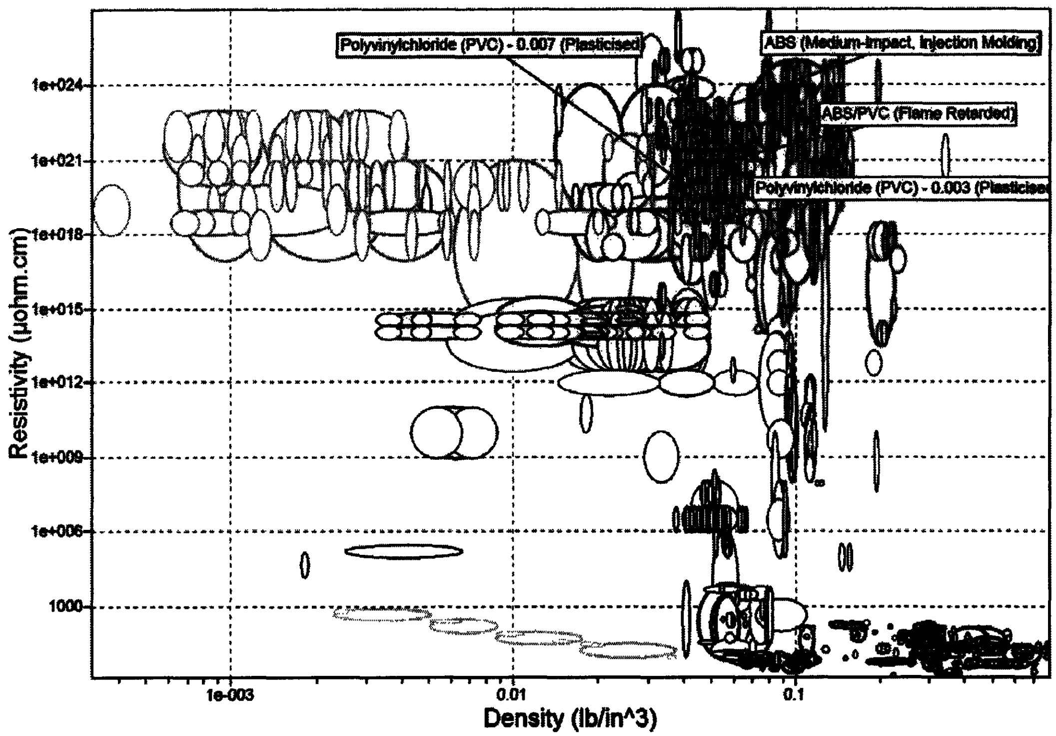

Figure 32. Resistivity vs. Density[70]

In this second graph, the primary focus is the density or weight of the material as resistivity as already been discussed. With the logarithmic scale, this graph shows that polymers (blue) are generally clustered between 0.02 – 0.08 lb/in^3 which is a fairly small range. Consequently, the type of polymer does not matter significantly when comparing weight, and in particular, PVC and ABS are only approximately 0.01 lb/in^3 apart thus confirming PVC as the better material for the purpose of housing the transmitter and receiver.

There are many materials that are significantly less dense than polymers, but are unsuited for the purpose of housing the transmitter. These bright green materials are the foam polymers. Referring back to the "Typical Ashby Diagram" (Figure 28), the strength of foam polymers lies in the upper left hand corner, so while the least dense, foam polymers also have a low Young's Modulus. Consequently, these foams deform easily under low amounts of stress; over time these foams will undergo more permanent deformation and will therefore have a shorter lifetime than other polymers. The dark blue materials are also foam materials, but are instead foam ceramics. For the same

[70] Chai, Shutsu (2006). Resistivity vs. Density, PVC & ABS Labeled. Cambridge Engineering Selector, Granta Design. dens-resist-PVC-label.jpg. Cambridge. **1602 x 1155.**

reasons, foam ceramics would not be appropriate for this portion of the housing. The following two graphs confirm the mechanical properties of foams that limit their usefulness. The first graph plots fracture toughness against density (Figure 33).

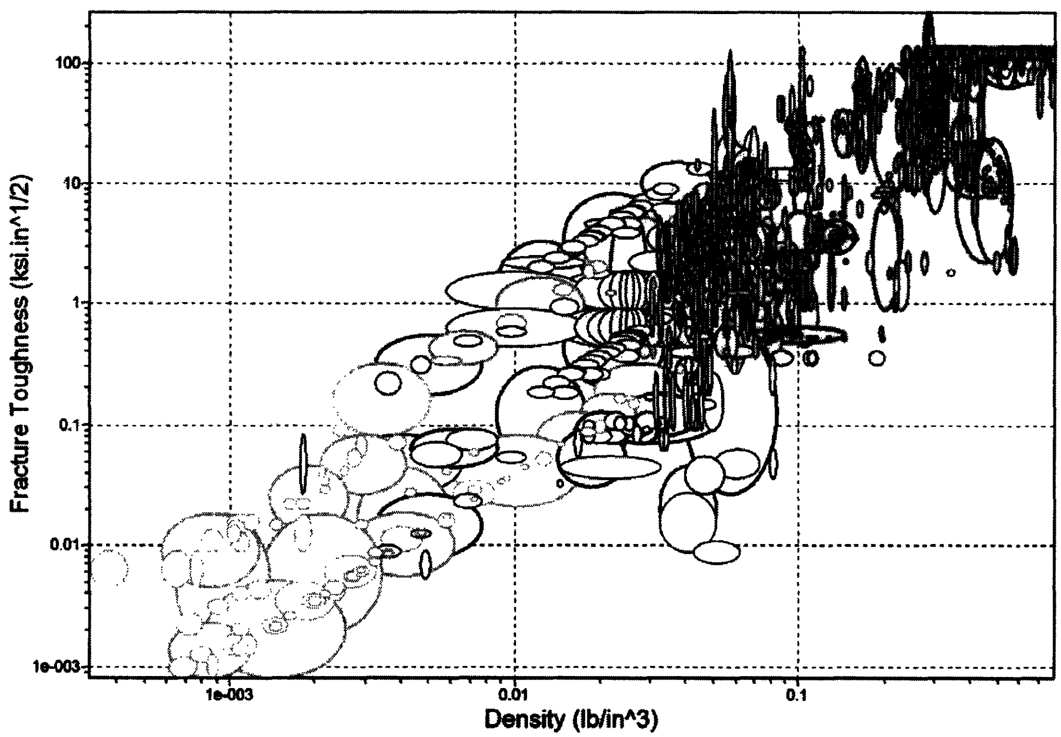

Figure 33. Fracture Toughness vs. Density, Foams in Lower Left[71]

Fracture toughness is a measure of the resistance of the material to the propagation of a crack.[72] Most of the foams fall in the lower third of all materials. With repeated movements in this rearrangeable system, the housing needs to be able to withstand fracturing with repeated stress in spite of potential cracks.

The next figure looks at the materials distribution based on Vickers Hardness, again with density on the x-axis to maintain continuity between these figures (Figure 34).

[71] Chai, Shutsu (2006). Fracture Toughness vs. Density. Cambridge Engineering Selector, Granta Design. Cambridge. **1619 x 1144.**

[72] "Glossary of Materials Attributes."(2005). Cambridge Engineering Selector Retrieved April 6, 2006, from http://www.grantadesign.com/resources/materials/glossary.htm.

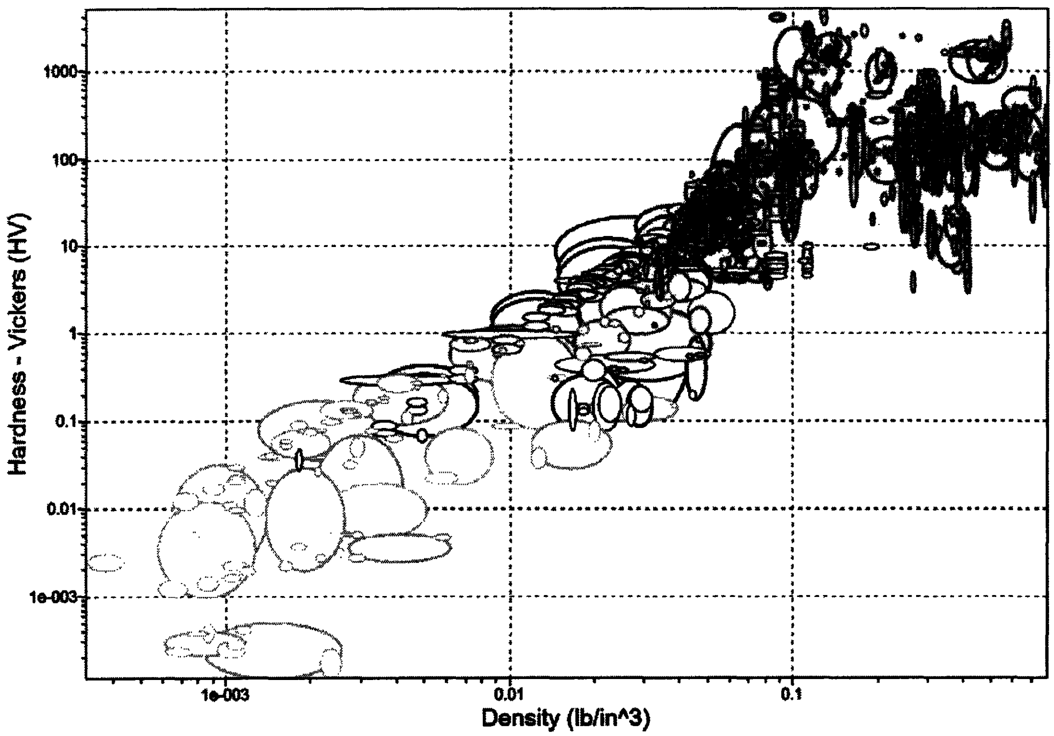

Figure 34. Vickers Hardness vs. Density[73]

Vickers Hardness is measured by pressing a pointed diamond into the surface of a material and then dividing the force required to create the indent divided by the projected area of the indent. As the foam polymers mostly appear in the lower left-hand corner of the figure above where hardness is particularly low because this is a logarithmic scale, this assessment of materials concludes that the damageability of foam materials is sufficient to remove them from the pool of potential materials for the housing.

6.2.3 Column

As the largest component of the system because of its height, the column needs to be both strong to withstand deformation under incidental impact and lightweight to be easily moved. Consequently, the materials pool is narrowed by plotting the inverse of the Young's Modulus against density to filter out materials that are both stiff and lightweight. The following graph plots this relationship between stiffness and weight for the materials available in this database with potential materials labeled (Figure 35).

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[73] Chai, Shutsu (2006). Hardness (Vickers) v. Density. Cambridge Engineering Selector, Granta Design. Cambridge. **1598 x 1158.**

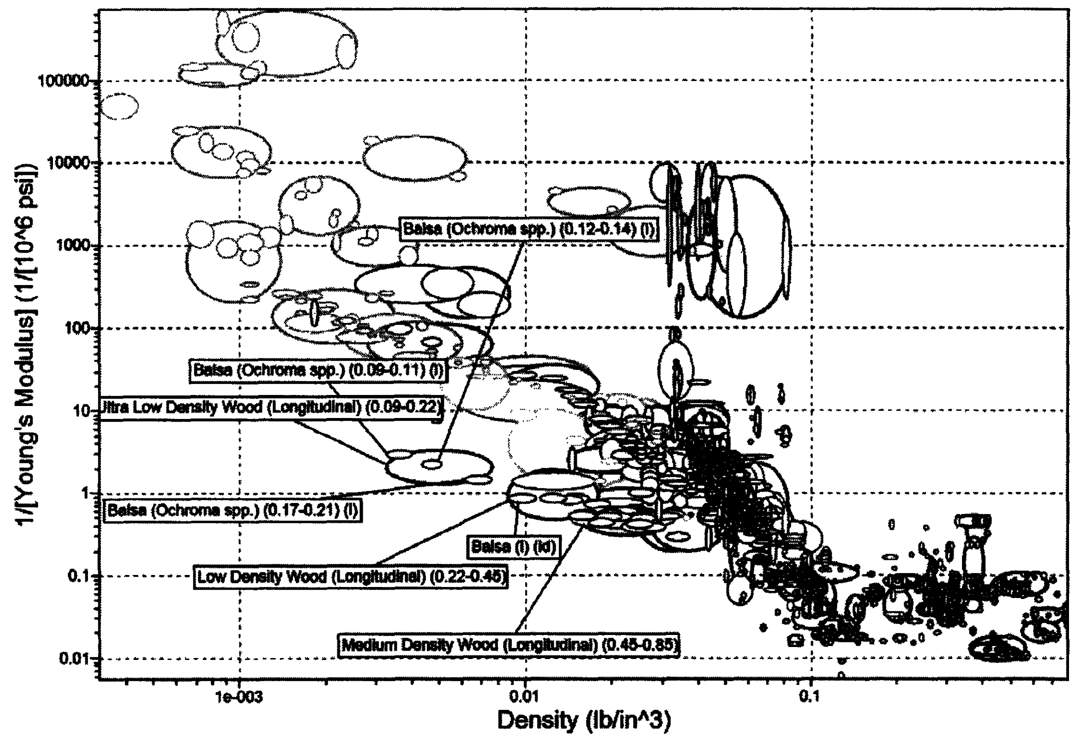

Figure 35. 1/Young's Modulus vs. Density, Potential Materials Labeled[74]

On this figure, the materials that are along the lowest edge of the trade-off curve are labeled; these are the lighter materials that still have a relatively high Young's Modulus as the vertical axis is the inverse of the Young's Modulus. These materials turn out to be several variations of balsa wood and ultra low density wood.

The other materials that fall around this area include aluminum foam and other heavier woods (Figure 36).

[74] Chai, Shutsu (2006). 1/Young's Modulus vs. Density, Potential Materials Labeled. Cambridge Engineering Selector, Granta Design. young-dens-wood-labels.jpg. Cambridge. **1614 x 1147**.

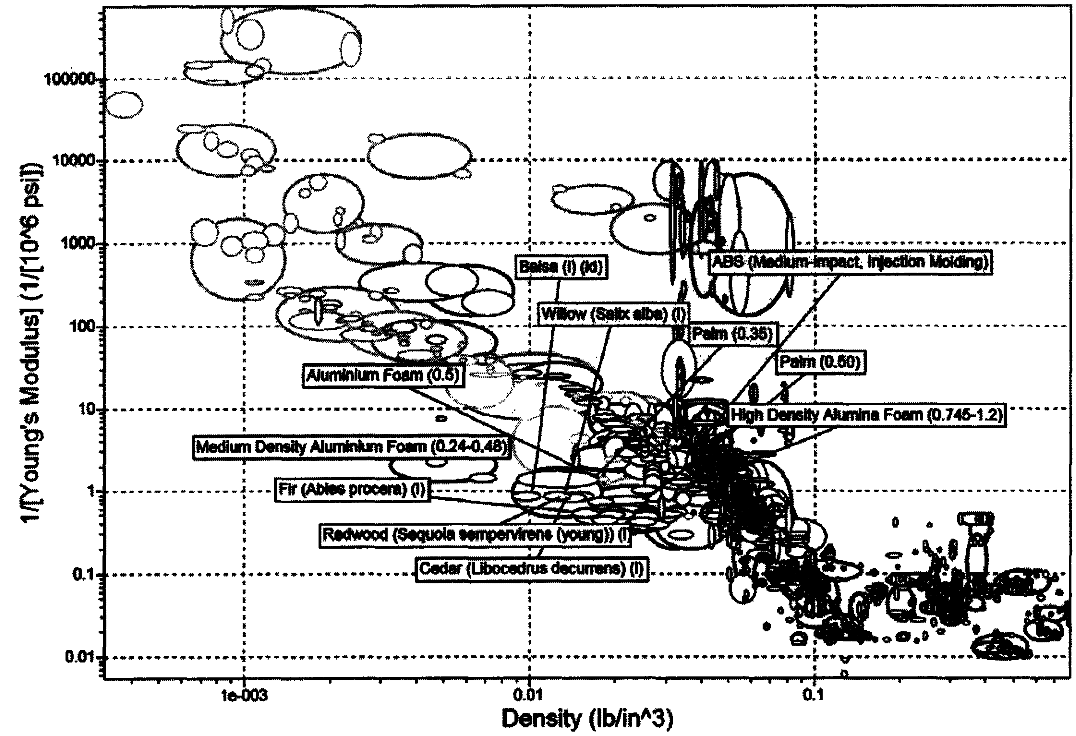

Figure 36. 1/Young's Modulus vs. Density, Additional Materials Labeled[75]

These materials are of approximately the same stiffness but are more dense and thus less lightweight. Because of the fibrous nature of most types of wood, the strength of these materials is particularly anisotropic; strength is much greater along the grain (longitudinally) than across the grain (transverse). This problem can be seen in a plot of shear strength against density (Figure 37).

[75] Chai, Shutsu (2006). 1/Young's Modulus vs. Density, Additional Materials Labeled. Cambridge Engineering Selector, Granta Design. young-dens-other-labels.jpg. Cambridge. **1617 x 1145.**

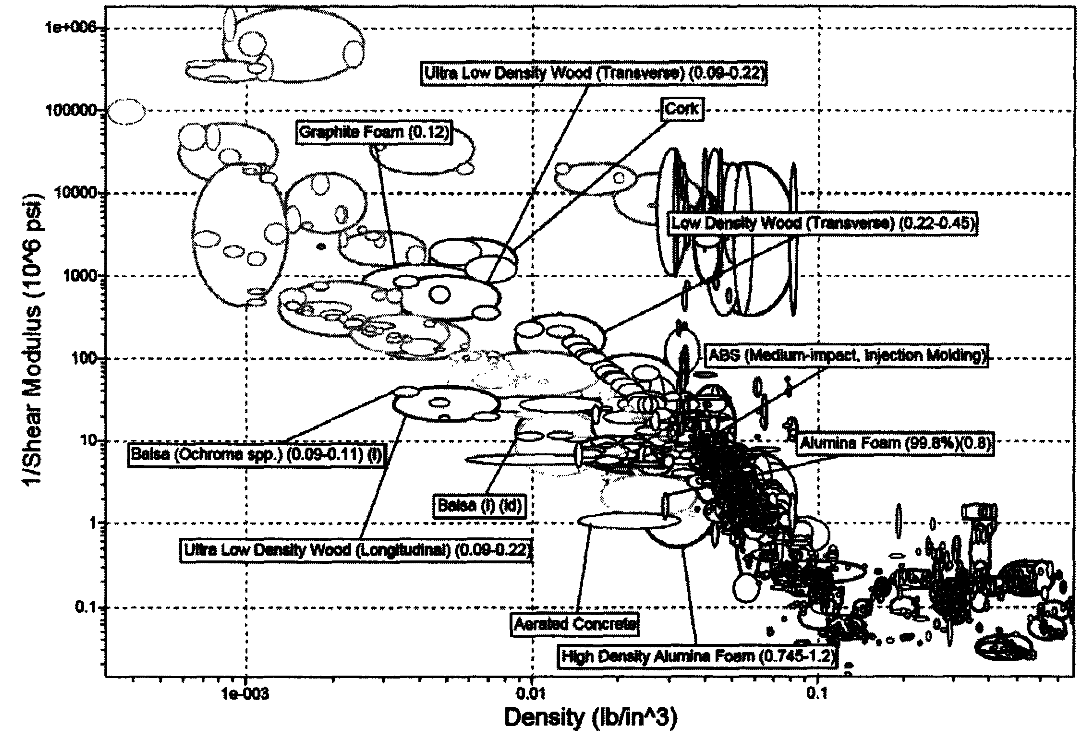

Figure 37. Shear Strength vs. Density, Woods Labeled[76]

The shear modulus of most woods are less than 0.1 x 10^6 psi which is relatively low. In terms of materials selection, there is not a significant impact as the column can be constructed with uniform loading on each part of the column to avoid shearing. In addition, as mentioned before, the longitudinal direction of wood is significantly stiffer than that of the transverse. The ultra low density wood in the figure above has both the transverse and longitudinal values labeled; the value of the shear modulus for the transverse direction is approximately 0.002 x 10^6 psi while its counterpart in the longitudinal direction is about twenty-five times greater at around 0.05 x 10^6 psi. Consequently, any wood used for these columns must be loaded longitudinally.

In light of the previous three figures, as concluded before, the column should be constructed of either ultra low density wood or balsa wood. With no clear advantage of one material over another, the final mode of evaluation will be the cost of the materials. The following figure plots cost against density (Figure 38).

[76] Chai, Shutsu (2006). Shear Strength vs. Density, Woods Labeled. Cambridge Engineering Selector, Granta Design. shear-dens-labeled. Cambridge. **1613 x 1147.**

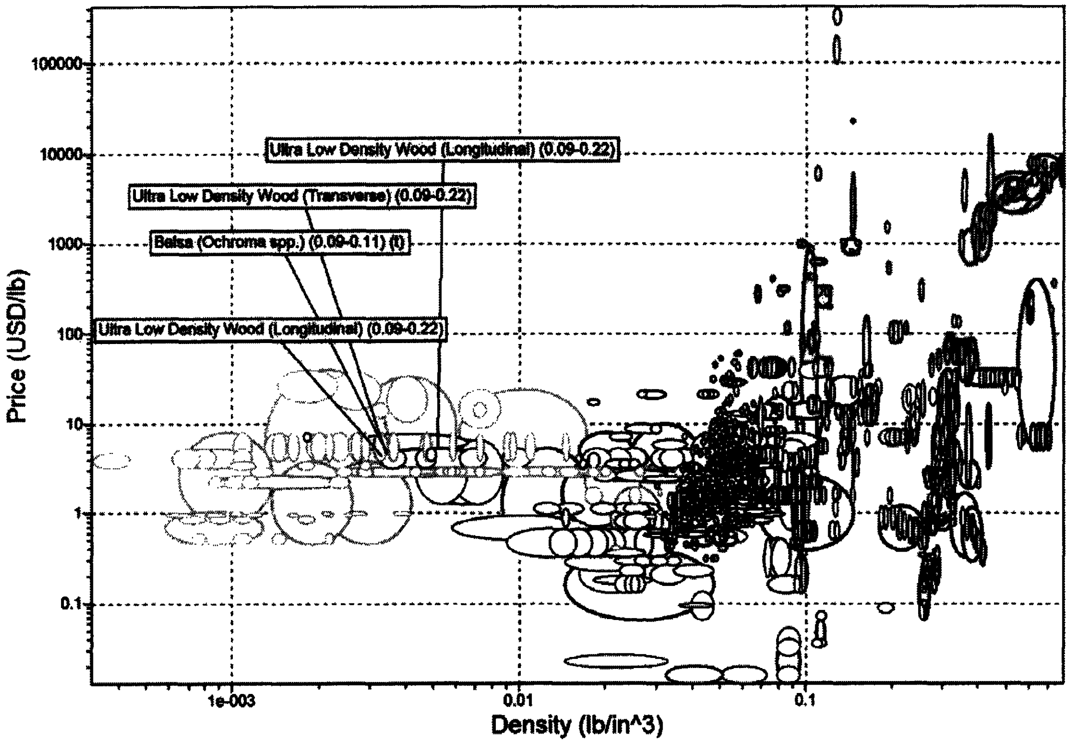

Figure 38. Price vs. Density, Balsa Compared to Ultra Low Density Wood

Through this figure, the cost per pound can be compared; both ultra low density wood and balsa wood span the same range on the price scale of United States Dollars per pound. While this does not provide any additional distinction through price per pound as hoped, this graph makes the difference in density variation more apparent. On this figure, ultra low density wood is labeled twice to demonstrate just a portion of the range of densities that this category spans; the labels attach at two different points along the wide oval that denotes ultra low density wood. This range goes significantly higher in density than does the range of the balsa wood. As the size and dimensions of the column have already been defined, the volume of the column structure has already been set; consequently, with a comparable cost per pound, the cost of each column increases linearly with density. By this logic, using a cost comparison, balsa wood will cost less because it is generally less dense. Thus, balsa wood will be an appropriate choice for the construction of the columns for this system.

Through the preceding discussion, balsa wood appears to be an ideal material for this lightweight system, yet experimental knowledge of balsa wood suggests otherwise; in past experiences with balsa, the material could often be characterized as "brittle" or easily crushed. High school physics competitions often used balsa wood as a challenging material for bridge-building because of its tendency to fracture when load is applied. With this experience in mind, this thesis will recommend balsa as a structural interlayer as opposed to the only material for the column.[77]

[77] Fernandez, John (2006). E-mail: The "brittle-ness" of Balsa Wood. S. Chai. Cambridge.

To verify this observation about the nature of balsa wood, the Modulus of Rupture is plotted against density. The Modulus of Rupture is also referred to as the flexural strength or torsional strength, where flexural strength is the "maximum fiber stress at failure" and torsional strength is the "maximum shear stress in the extreme member of a circular member at failure."[78] The purpose of examining these two properties against one another is to examine the modulus of rupture as a method to capture the tendency of balsa wood to break while using density on the x-axis places materials in a general location that is already familiar due to the previous figures that were also plotted against density. The following graph shows this relationship (Figure 39).

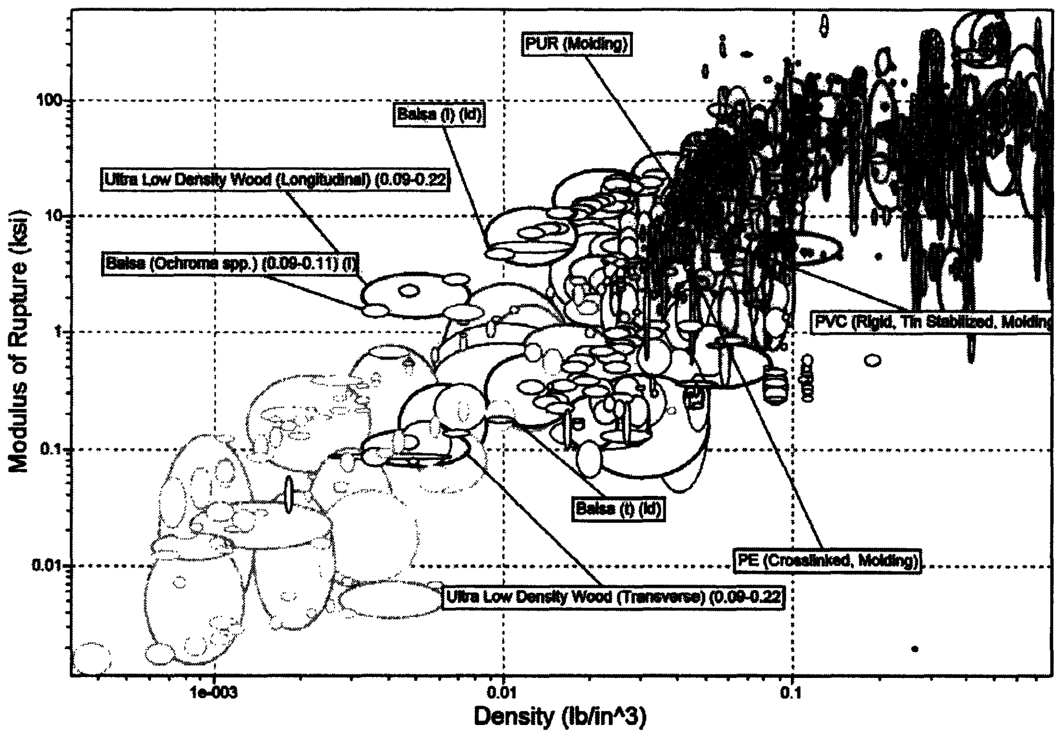

Figure 39. Modulus of Rupture vs. Density, Low Density Materials compared to Polymers (PUR = Polyurethane, PVC = Polyvinylchloride, PE = Polyethylene)

While at first glance, the modulus of rupture of balsa wood is actually comparable to that of several common polymers such as polyurethane (PUR), polyvinylchloride (PVC) or polyethylene (PE), a more in-depth look reveals that this is true longitudinal direction but not in the transverse direction. In the transverse direction, the modulus of rupture for balsa wood is up to approximately a hundred times smaller than in the longitudinal direction, confirming the "brittle" nature of balsa wood.

[78] ALPHA, ServoCon. "Glossary." Retrieved May 7, 2006, from http://66.207.86.189/web2005/support/glossary.htm.

To minimize this characteristic of balsa wood while still desiring its other properties, balsa wood can be used as a structural interlayer. Two common sandwich panels include carbon and fiberglass.[79] A quick comparison of costs online at The Composite Store, Inc. reveals that the fiberglass and balsa composite is approximately half the cost of the carbon and balsa composite.[80] Consequently, the material selected for the construction of the hallow column is a composite of fiberglass encased balsa wood.

6.2.4 Fabric Interior

For the fabric base, there are several basic options. The following table presents the potential materials, their relevant characteristics, and the advantages and potential uses of each.

Table 8: Common Flexible Materials[81]

Material [Common Examples]	**Relevant Characteristics**	**Advantages**	**Potential Use in System**
Nylon 6 [Kites]	Flame Resistant, Heavy thread and gridding prevents ripping	Good for outdoor uses, especially with windy conditions; durable	Walls
Ethylene-tetrafluoroethylene (ETFE) [Skylights]	Non-rigid, 98% transparent, strong in tension, UV resistant	Flexible glass substitute, malleable without fracture	Walls, Windows on deployed fabric
Polypropylene (PP)	Teflon-coated material (PP, PV, PE, PVC) is strong, Teflon prevents scratching (Teflon-coated PVC is also inexpensive)	Relatively high fracture toughness and tensile strength[82]	Walls
Polyethylene (PE)		Two most produced synthetic polymers	Walls
Polyvinylchloride (PVC)			Walls: when coated with Teflon, can serve as a structural fabric
Fiber-reinforced Mylar [Latest sailing technology]	Mylar = tough sheet plastic	Can be translucent, different colors	Walls

These polymers can be compared for their tensile strength and fracture toughness, two measures of their performance under constant tension between the two columns and the repetitious process of being rolled and unrolled. The following table notes each of these six materials (Figure 40).

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[79] The Composites Store, Inc. (May 8, 2006). "Balsa Core Composites." from http://cstsales.web01.yourhost.com/shop-bin/sc/productsearch.cgi?storeid=*1a43ce414170ce6a13a769ef894bfc.

[80] Ibid. Prices at The Composites Store, Inc. for a 5.75" x 5.75" piece of composite, 0.25" thick: fiberglass = $10.10, carbon = $20.05.

[81] Fernandez, John (2005). Meeting with Professor Fernandez. S. Chai. Cambridge: Materials survey with Professor Fernandez. .

[82] Chai, Shutsu (2006). Polymer Comparison for Fabric Interior. Cambridge Engineering Selector. Cambridge. **1568 x 1180**.

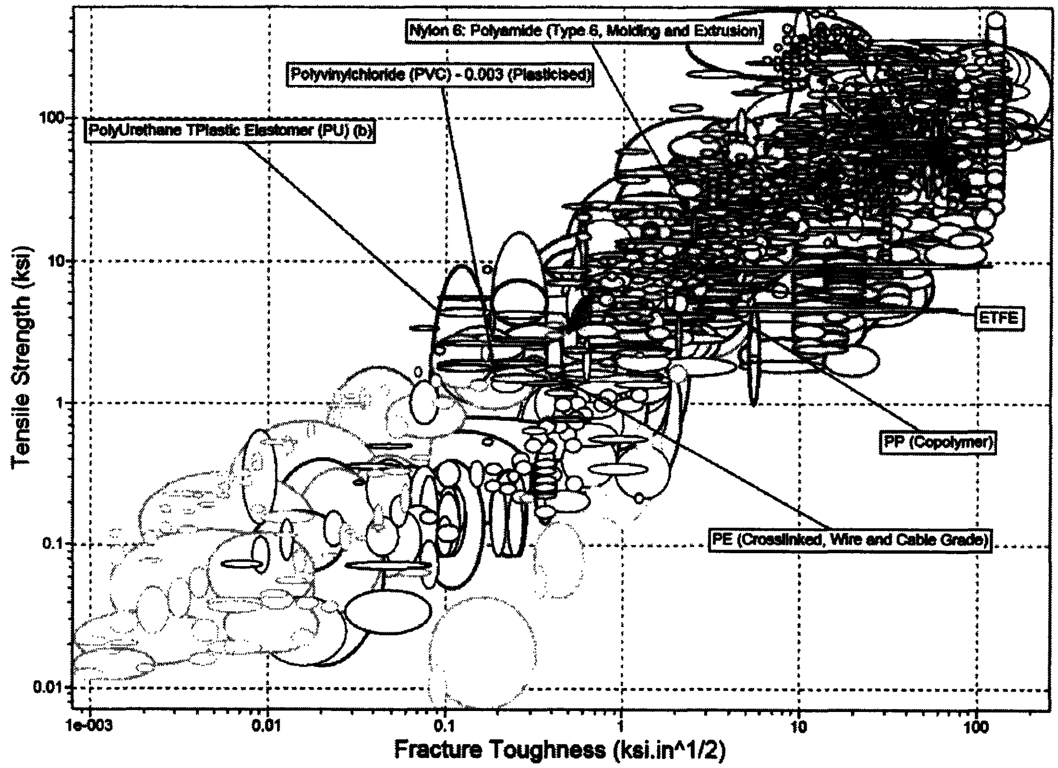

Figure 40. Polymer Comparison for Interior Fabric Selection

In the preceding figure, the ideal material would lie in the upper right corner, with a high tensile strength, a measure of a materials endurance when stretched between two columns, and a high fracture toughness, a measure of the fatigue-life of a material. Thus, through the location of each of these materials on this graph, the best choice is shared by two materials: Nylon 6 and ETFE. Rather than selecting one over the other, this thesis proposes a combination where Nylon 6 serves as the base material and ETFE serves as a transparent window material.

In addition to these fabric materials, there are also several more unusual, dynamic and innovative materials. The following table discusses each material briefly.

Table 9: Unusual Flexible Materials

Material	Relevant Characteristics	Advantages	Disadvantages
Thin-film LCD Displays	Digital Image display like a TV.	Can display images	Still very small in size at the moment;[83] LCDs are sensitive to humidity and temperature change, easily scratched, sensitive to vibration [84]
Luminescent Surfaces	Surfaces can emit light	Solution to sufficient lighting in space	Only intensity can be variable, not display or color.
Thermochromic Polymers	Temperature change causes a color changes	Can temporarily record the whereabouts of people in the reprogrammable system	
Translucent/Transparent Types	Opacity changes with temperature or current flow	Interior display spaces can be visible through a secure barrier	Can never become completely opaque.[85]

Many of the more unusual and versatile materials are only beginning to emerge with the evolution of technology. The unique design of this system allows the fabrics to be changed over time as new fabric technology emerges, which adds yet another layer of flexibility to this system. Flexible thin-film LCD (liquid crystal display) display technology has only been perfected in the last year to the point where display is true to the image in spite of bending; on November 28, 2005, Samsung announced the development of the largest flexible screen yet, which was only a mere seven-inch screen, a piece far smaller than a complete wall for this 30-foot high system.[86] While at the moment, flexible LCD technology is still evolving and improving, eventually, this material may allow the greatest flexibility in wall technology as the display surface can constantly be programmed with changing digital projections, thus most closely supporting the goals of The Museum of the Mile and The Digital Mile.

6.2.5 Fabric Exterior

The exterior edge fabric has two requirements that must be met: weather-tightness and security. Other additional requirements that are not as necessary but that also fall under the "Exterior Standards" category include corrosion resistance, UV radiation resistance and non-flammability.

In this case, the security of the fabric refers to whether the fabric can be forcefully penetrated. Weather-tightness refers primarily to water resistance. The last three characteristics, corrosion resistance, UV radiation and non-flammability, in addition to weather-tightness, will likely be a fabric coating that gives all of these properties to the fabric. Thus, based on the earlier discussion of interior fabrics, the fabric base for the

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[83] LeClaire, Jennifer (2005) "Samsung Develops Flexible LCD Display." Tech News World **Volume**, DOI:
[84] Plasma.com. "Learn About LCD TV and TFT LCD Displays." Retrieved April 26, 2006, from http://www.plasma.com/classroom/what_is_tft_lcd.htm.
[85] Compagno, Andrea (1995). Intelligent Glass Façades: Material, Practice, Design. Berlin, Birkhäuser Verlag.
[86] LeClaire, Jennifer (2005) "Samsung Develops Flexible LCD Display." Tech News World **Volume**, DOI:

exterior should also be of Nylon 6 which has a heavy thread and gridding that is good for outdoors as the heavy weave helps to endure the outdoor winds and forces. In addition, this material is flame resistant, another important characteristic for protecting the interior of The Museum of the Mile. As the rest of the desired environmental characteristics can be achieved through a material coating, the issue of security becomes the primary concern for the exterior fabric.

In order to create a fabric that is sufficiently secure, the fabric will be interwoven with stainless steel fibers. Stainless steel is selected as stainless steel resists corrosion better and has a higher environmental resistance. The steel fibers reinforce the weave of the fabric to create a flexible yet impenetrable exterior wall. Kevlar or aramid fiber is often used to strengthen fabrics, but do not make them impenetrable. Tensile strength has no bearing on whether the Kevlar fibers can be severed. While not useful to reinforce material, Kevlar can be useful as the base fabric; Kevlar is particularly useful because of its low flammability. While these aramid fibers do not resist UV degradation, a Teflon coating will be sufficient to provide the environmental resistance necessary for this exterior surface. Derived from the Cambridge Engineering Selector to validate the use of a Teflon coating, the environmental resistance of Teflon, also known as polytetrafluoroethylene (PTFE – 25% glass fiber) is shown in the following table.

Table 10: Environmental Resistance of Teflon (PTFE), Cambridge Engineering Selector[87]

Property	Rating	Relevance
Flammability	Very Good	Important for protecting museum content
Fresh Water	Very Good	Resistance to rain and humidity
Organic Solvents	Very Good	Resistance to cleaning solvents
Oxidation at 500C	Very Poor	Little relevance – near impossible condition for system
Sea Water	Very Good	Unlikely condition
Strong Acid	Very Good	Unlikely condition
Strong Alkalis	Average	Resistance to cleaning solvents
UV	Good	Important as an outdoor surface
Wear	Good	Important with repeated use, as an outdoor surface
Weak Acid	Very Good	Resistance to acid rain
Weak Alkalis	Very Good	Resistance to cleaning solvents

6.2.6 Remaining Mechanisms

For the remaining mechanisms, stainless steel will serve the system well for its strength and environmental resistance. The following table demonstrates its environmental resistance that will ensure the system parts a long lifetime.

[87] Design, Granta (2001). CES Engineer Pro. CES Selector 3.2. Cambridge, Granta Design Limited: Materials Selection Software.

Table 11: Environmental Resistance of Stainless Steel, Cambridge Engineering Selector[88]

Property	Rating	Relevance
Flammability	Very Good	Important for protecting museum content
Fresh Water	Very Good	Resistance to rain and humidity
Organic Solvents	Very Good	Resistance to cleaning solvents
Oxidation at 500C	Very Good	Little relevance – near impossible condition for system
Sea Water	Very Good	Unlikely condition
Strong Acid	Good	Unlikely condition
Strong Alkalis	Very Good	Resistance to cleaning solvents
UV	Very Good	Important as an outdoor surface
Wear	Good	Important with repeated use, as an outdoor surface
Weak Acid	Very Good	Resistance to acid rain
Weak Alkalis	Very Good	Resistance to cleaning solvents

In addition to a strong environmental resistance, stainless steel also has other mechanical properties that make it suitable for this system. As many of these parts will bear the weight of the column it will be useful to calculate the potential weight of the column to ensure that stainless steel is sufficiently strong to carry the weight with a safety factor of two (Figure 41).

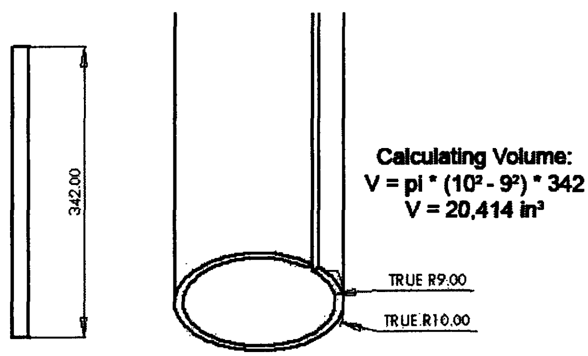

Figure 41. Column with Dimensions for Volume Calculations

From the Cambridge Engineering Selector, the maximum density of balsa wood is 0.01084 lb/in^3. Thus, the weight of the column without the fabric inside is 221.3 lbs. With a safety factor of 2, the column carriage must carry approximately 443 lbs. The following table shows the Young's Modulus and Tensile Strength of stainless steel which will both be sufficient to support the column.

[88] Ibid.

Table 12: Stainless Steel Material Properties[89]

Young's Modulus	27.41 – 29.73 x 10^6psi
Tensile Strength	62.37 – 105.9 ksi

[89] Ibid.

7. Conclusion

Through this thesis, a new building-edge has been designed to increase the flexibility of the front of The Museum of the Mile, a part of the proposed Digital Mile in Zaragoza, Spain. While this design study is specific to this museum, the concept of flexible space using reprogrammable architecture is an idea that can be transplanted to many other situations. Beyond the physical designs for this new building-edge, this design study has also demonstrated the need for and usefulness of a broader scope of knowledge for the design of responsive architectural environments.

This design project responded to the needs of The Museum of the Mile to develop an interactive and responsive space and thus creating a space with greater flexibility than the typical static building-edge. The design of paired movable columns and fabric deployed between each pair allows this system to create an incredible number of configurations, molding spaces to meet the demands of a diverse array of activities. The study of potential architectural designs has only begun to tap the variety of shapes and spaces. The nature of this flexible design allows the system to be modified as necessary to meet the needs of each new situation.

Further study may include developing a more weather tight system that need not remain in a moderate climate. In addition, as new materials and technologies are developed over time, the flexibility of the materials themselves can be increased, thus contributing further to the flexibility of the space. Particularly interesting for this space in The Museum of the (Digital) Mile is the future development of flexible liquid crystal displays; as the size of these materials increase the point of being a potential deployable fabric of this system, even the walls can become digital.

Beyond the presented architectural and mechanical designs of this reprogrammable system, this thesis has demonstrated the importance of integrating expertise and knowledge across disciplines. For this responsive environment, the active properties present a design problem beyond the typical scope of architecture, creating a greater burden to approach design with a broader scope of knowledge. This thesis has shown the need for the urban planner to identify a need, the architect to develop a design concept and architectural program, and the engineer to both broaden and limit the potential architectural designs as well as to develop the mechanical design.

Furthermore, outside the scope of the expertise of a mechanical engineer and planner is the work of an electrical engineer and computer programmer: this system undoubtedly is sufficiently complex that the electrical engineer and programmer would be need for the computer system and electronic components that would serve as the intelligence center of this system to drive and organize movement.

It has been through the feedback between the three disciplines of planning, architecture and engineering that this thesis has developed this rich and detailed design. This unique interactive and flexible space may even have uses far beyond this immediate situation at The Museum of the Mile. In fact, this design may be transplanted into many other systems, whether they are other building-fronts or large interior spaces with boundaries or various climates, each with their own environmental conditions. With each new situation, if similarly diverse expertise is applied to its design, this thesis has confirmed that the richness and thoroughness of design will ensure an appropriately designed system to increase the usefulness of a single space. If still more disciplines such as electrical engineering or computer science are drawn from for the design of such systems, the possibilities for robust and innovative building-design can and will reach far beyond the scope and depth of this thesis.

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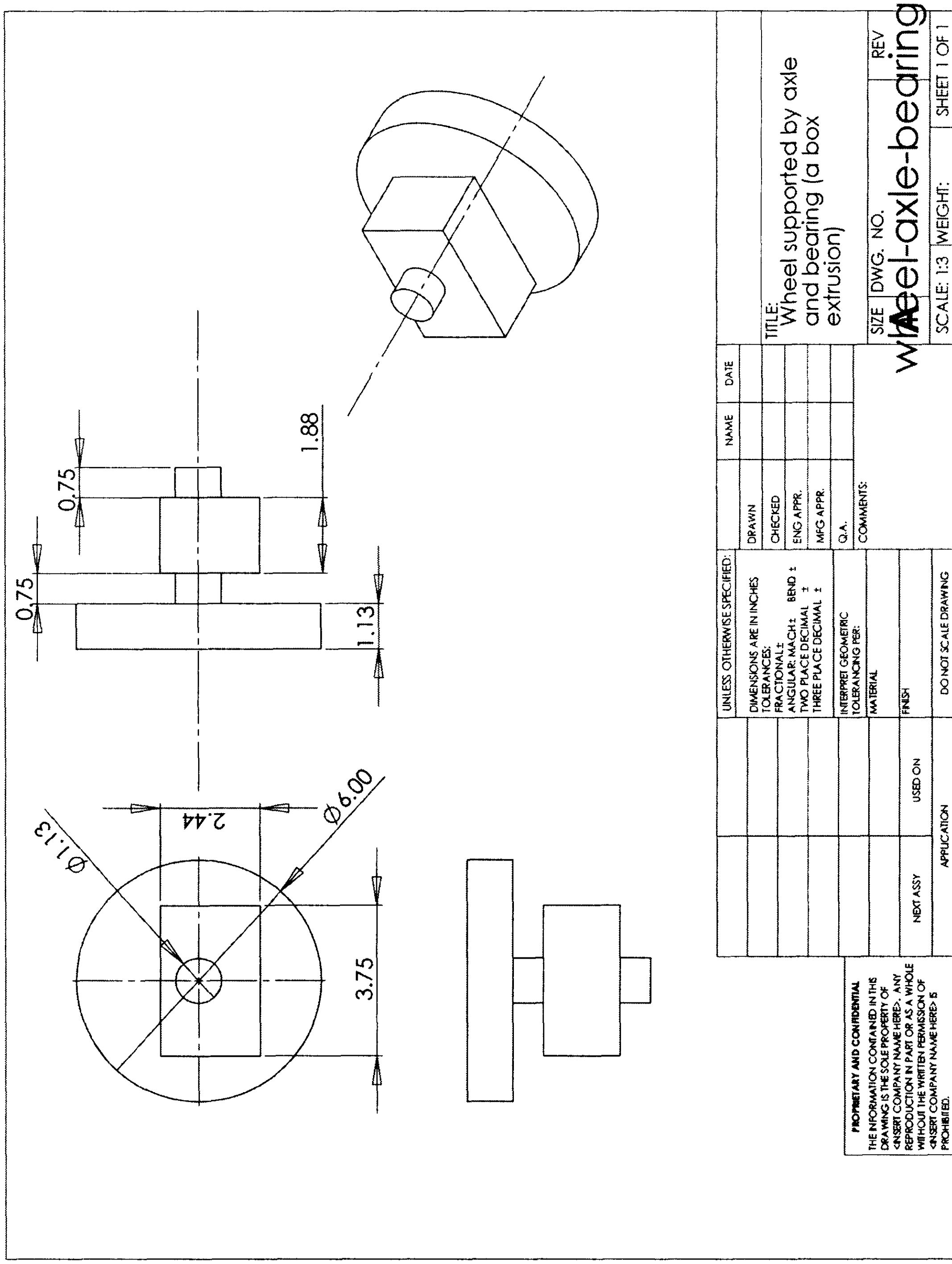
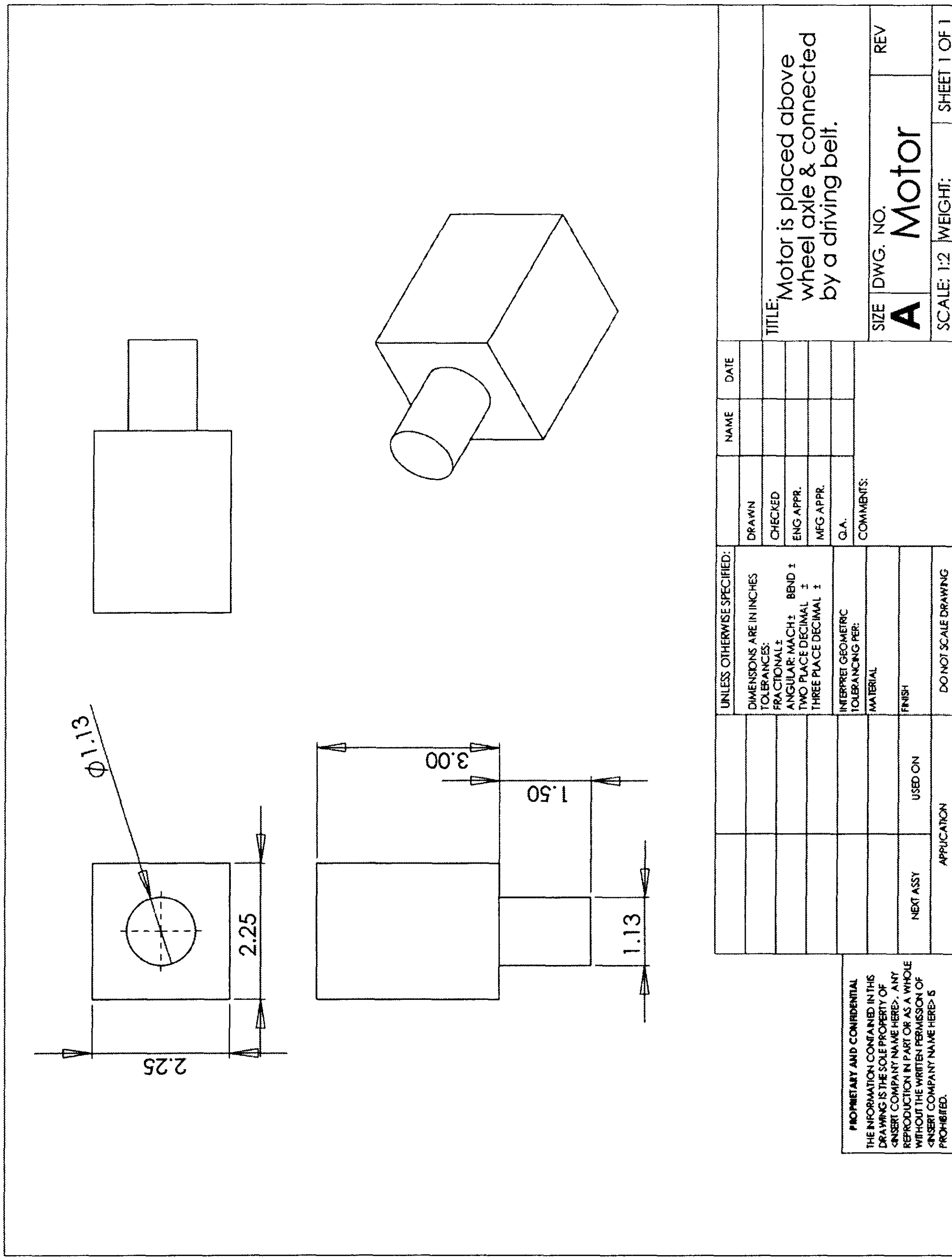
Appendix A: Movement Mechanisms (above Column) Drawings





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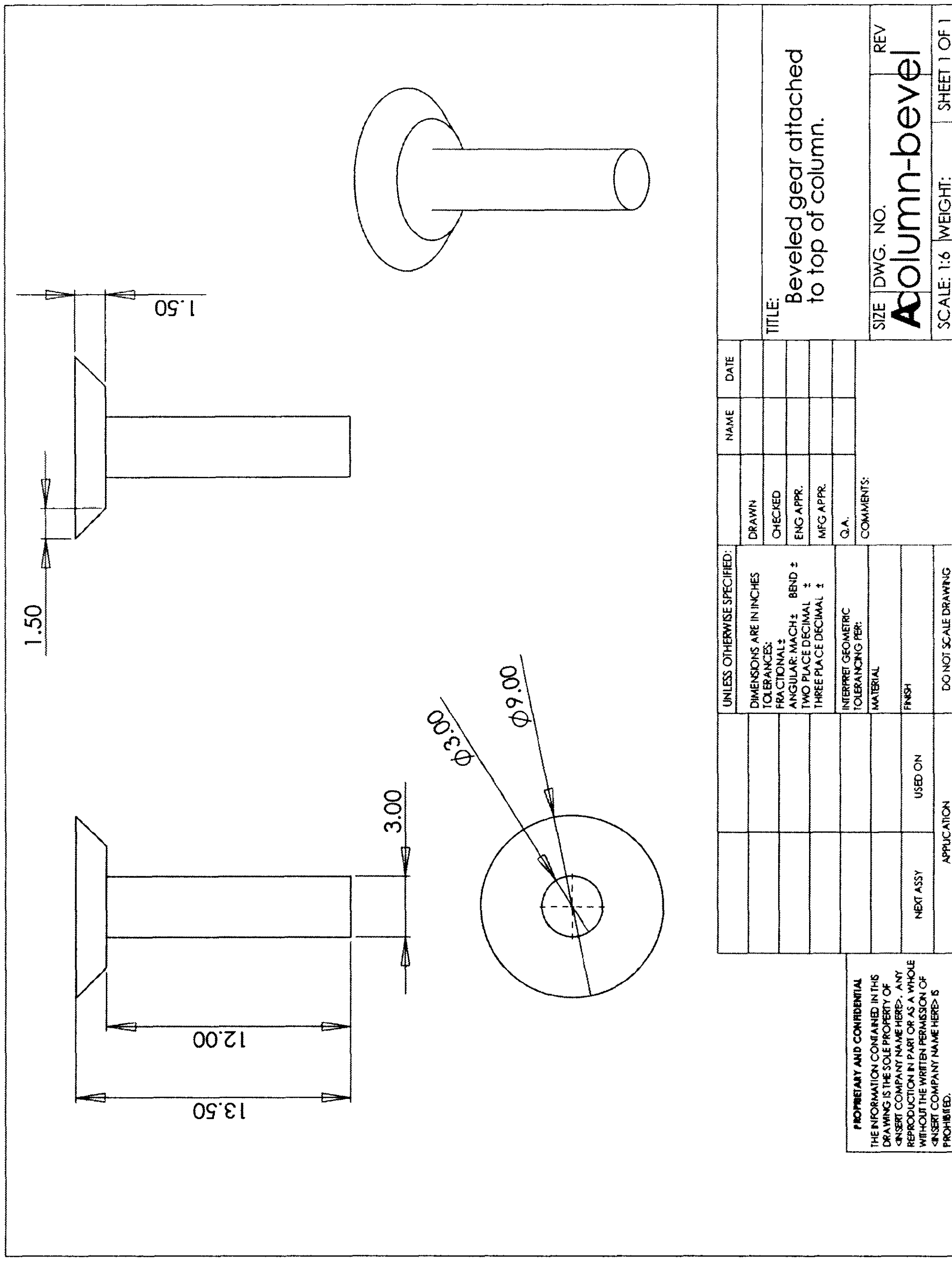

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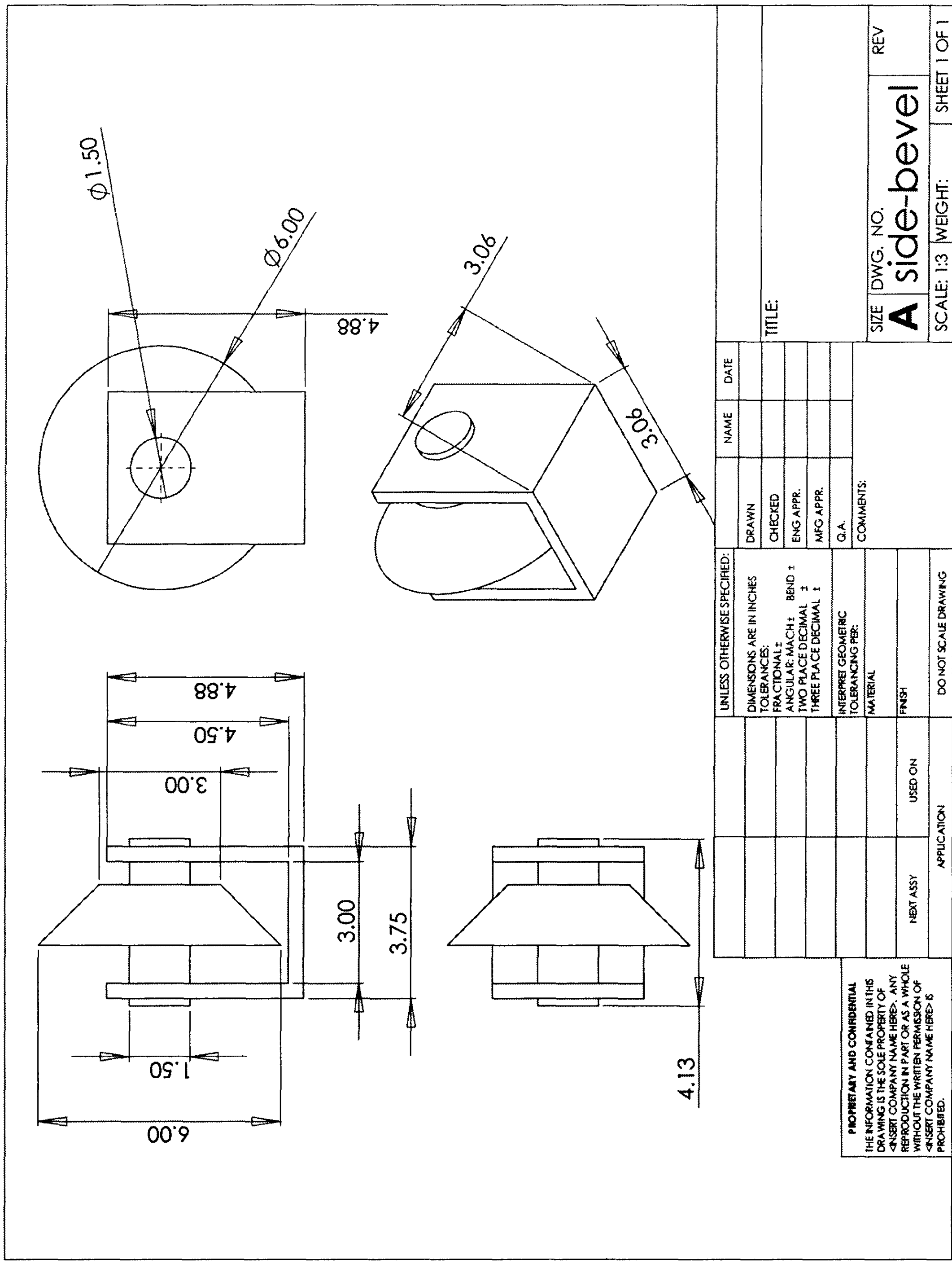
Ø1.50
Ø6.00
4.88
3.06
3.06
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4.50
3.00
3.00
3.75
1.50
6.00
4.13
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
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INTERPRET GEOMETRIC TOLERANCING PER:
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DO NOT SCALE DRAWING
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ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
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TITLE:
SIZE
DWG. NO.
A
side-bevel
REV
SCALE: 1:3
WEIGHT:
SHEET 1 OF 1
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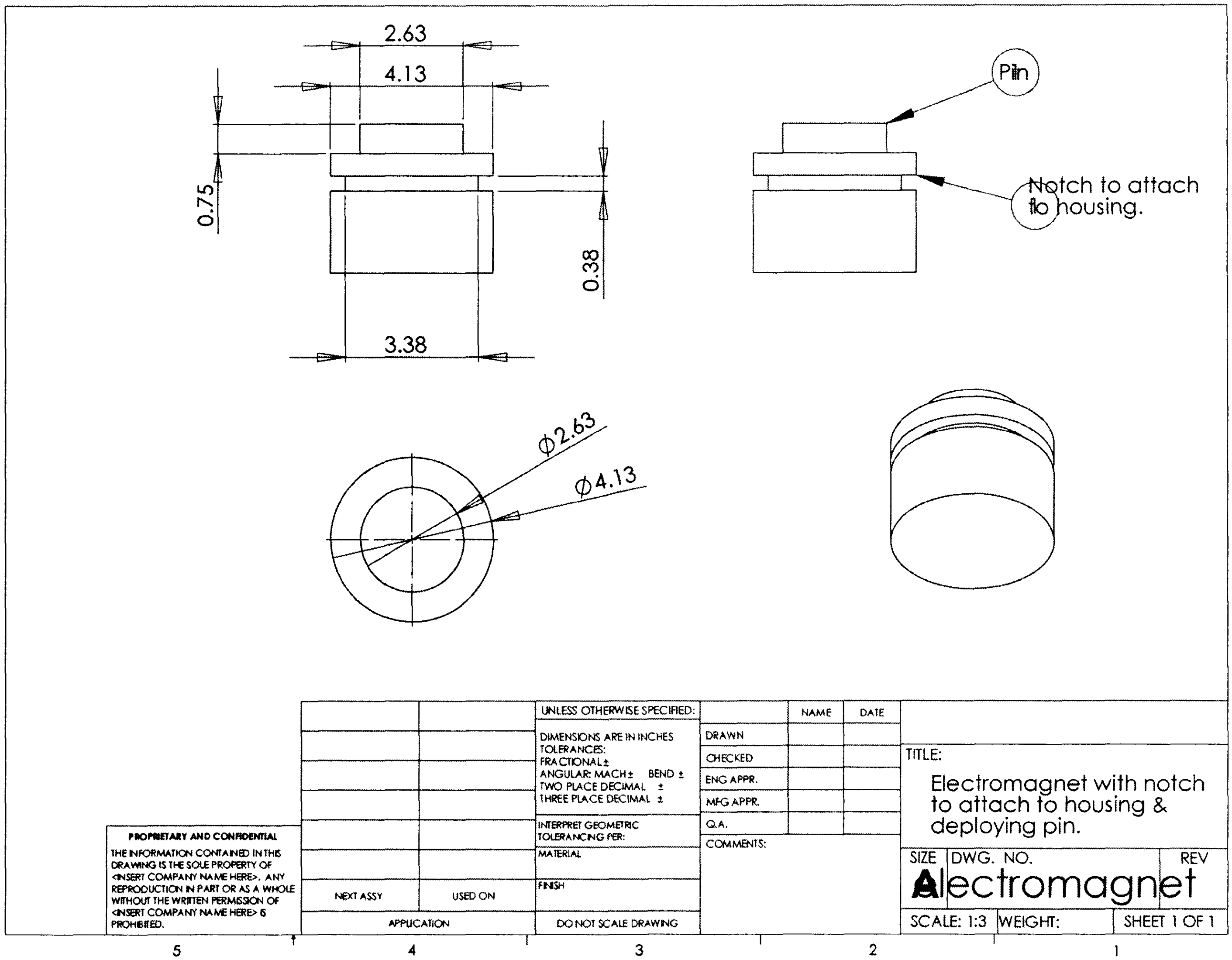
2.63
4.13
0.75
0.38
3.38
Piln
Notch to attach
to housing.
ϕ2.63
ϕ4.13
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
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THREE PLACE DECIMAL ±
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ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
Electromagnet with notch to attach to housing & deploying pin.
SIZE
DWG. NO.
REV
A
Electromagnet
SCALE: 1:3
WEIGHT:
SHEET 1 OF 1
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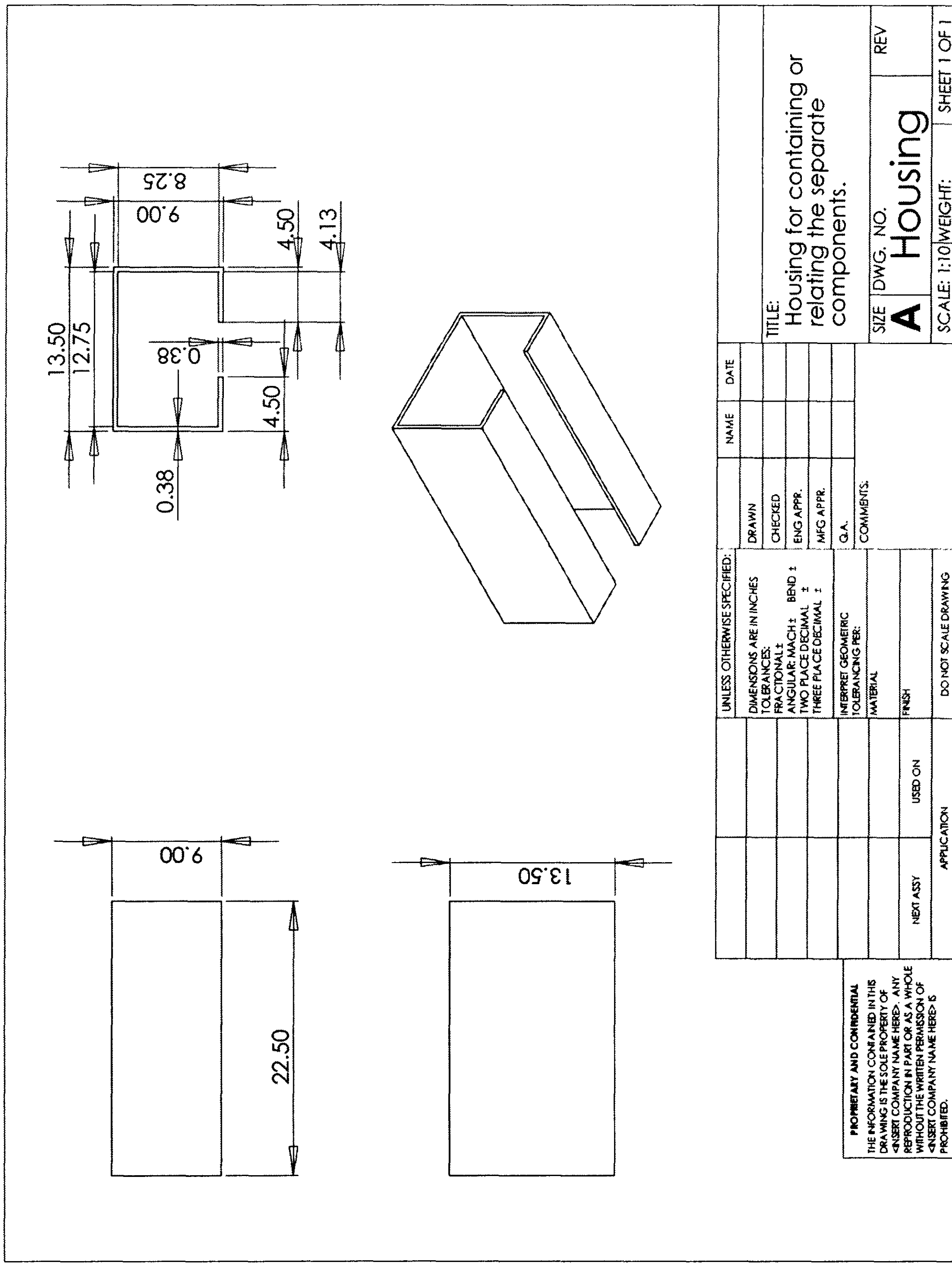
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4.50
4.13
0.38
0.38
4.50
9.00
22.50
13.50
TITLE:
Housing for containing or relating the separate components.
SIZE
A
DWG. NO.
Housing
REV
SCALE: 1:10
WEIGHT:
SHEET 1 OF 1
NAME
DATE
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CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
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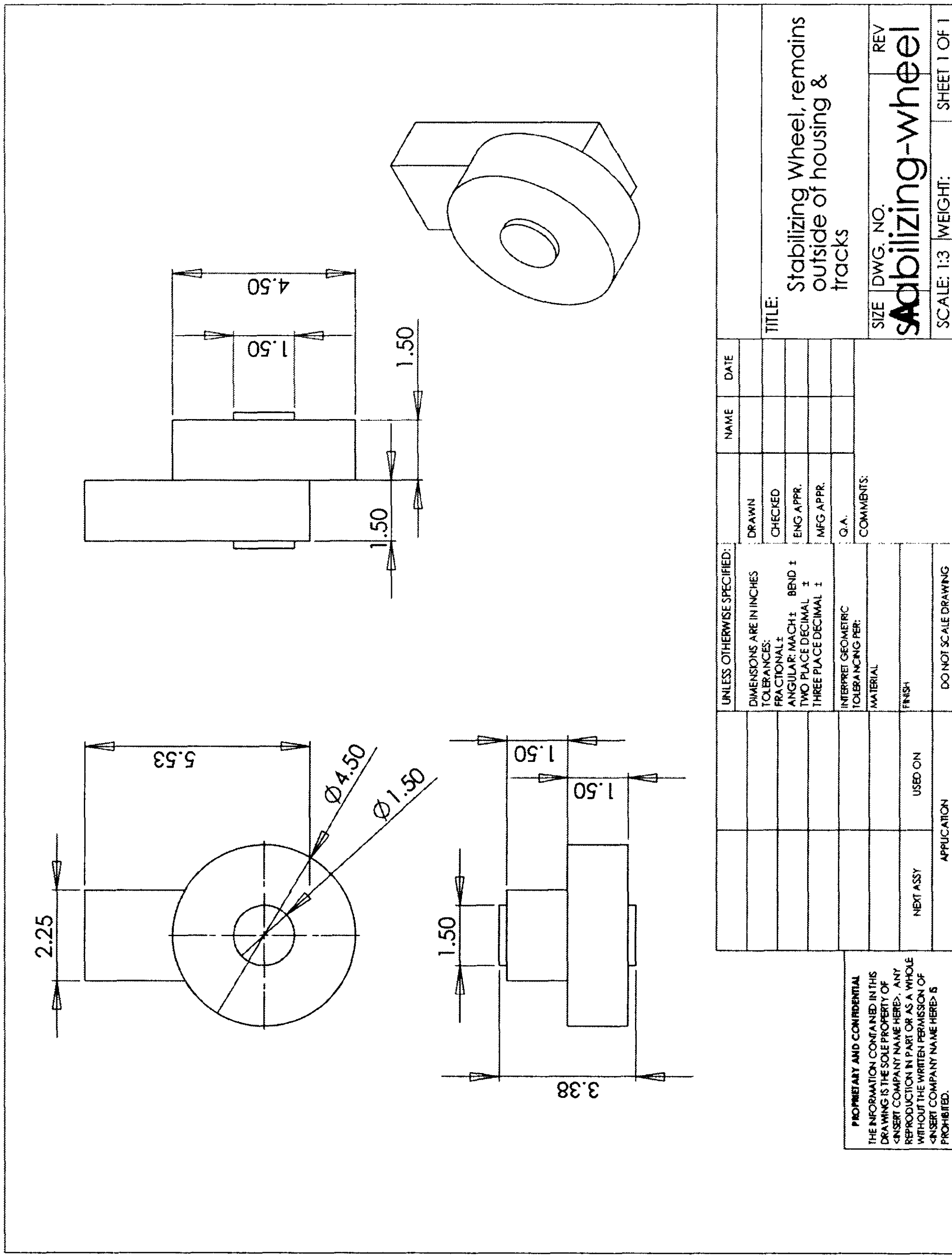

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DIMENSIONS ARE IN INCHES
TOLERANCES:
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ANGULAR: MACH ± BEND ±
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THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
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DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
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CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
Stabilizing Wheel, remains outside of housing & tracks
SIZE
A
DWG. NO.
stabilizing-wheel
REV
SCALE: 1:3
WEIGHT:
SHEET 1 OF 1
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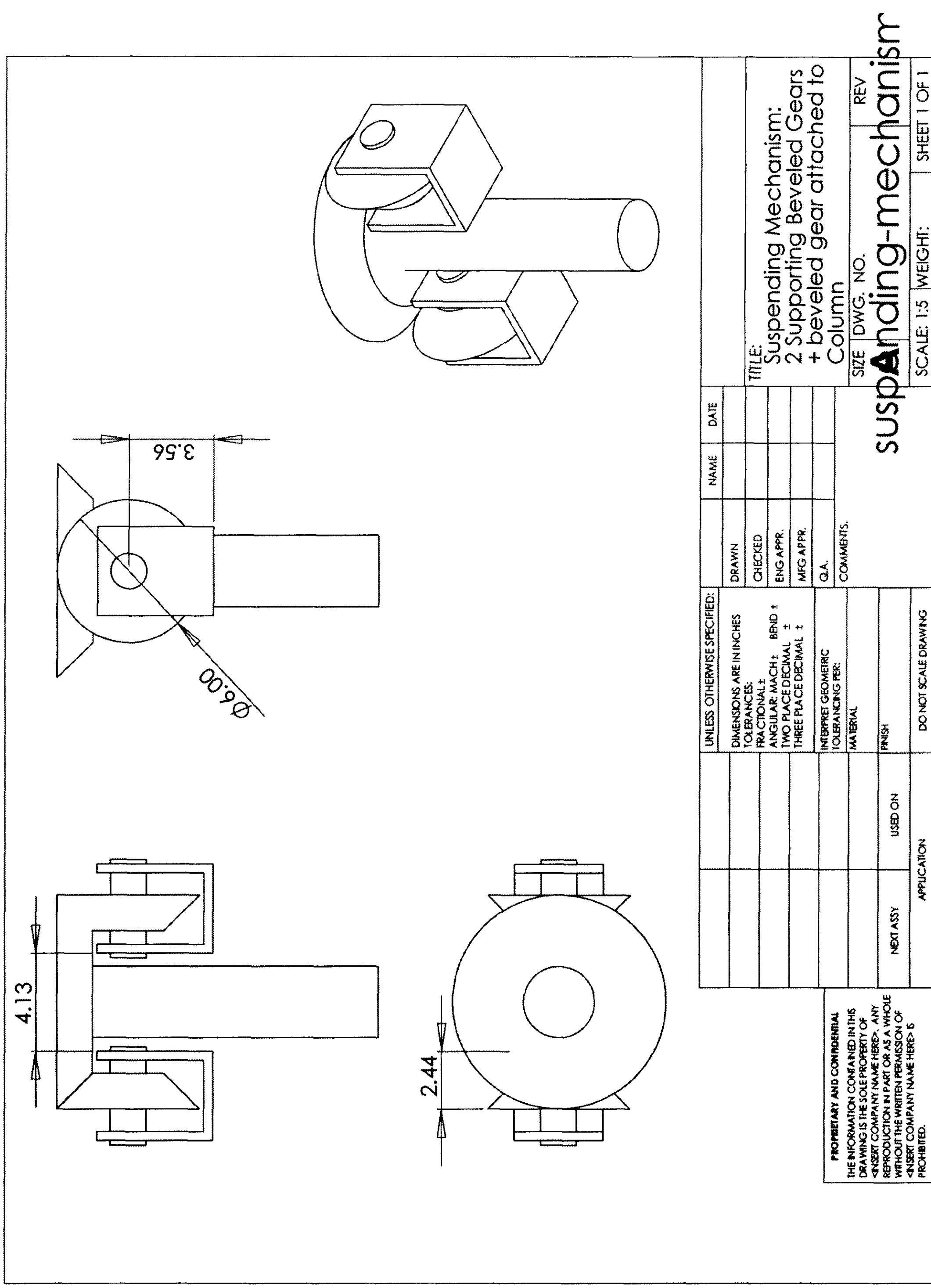
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TOLERANCES:
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ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
TITLE:
Suspending Mechanism: 2 Supporting Beveled Gears + beveled gear attached to Column
SIZE
A
DWG. NO.
suspending-mechanism
REV
SCALE: 1:5
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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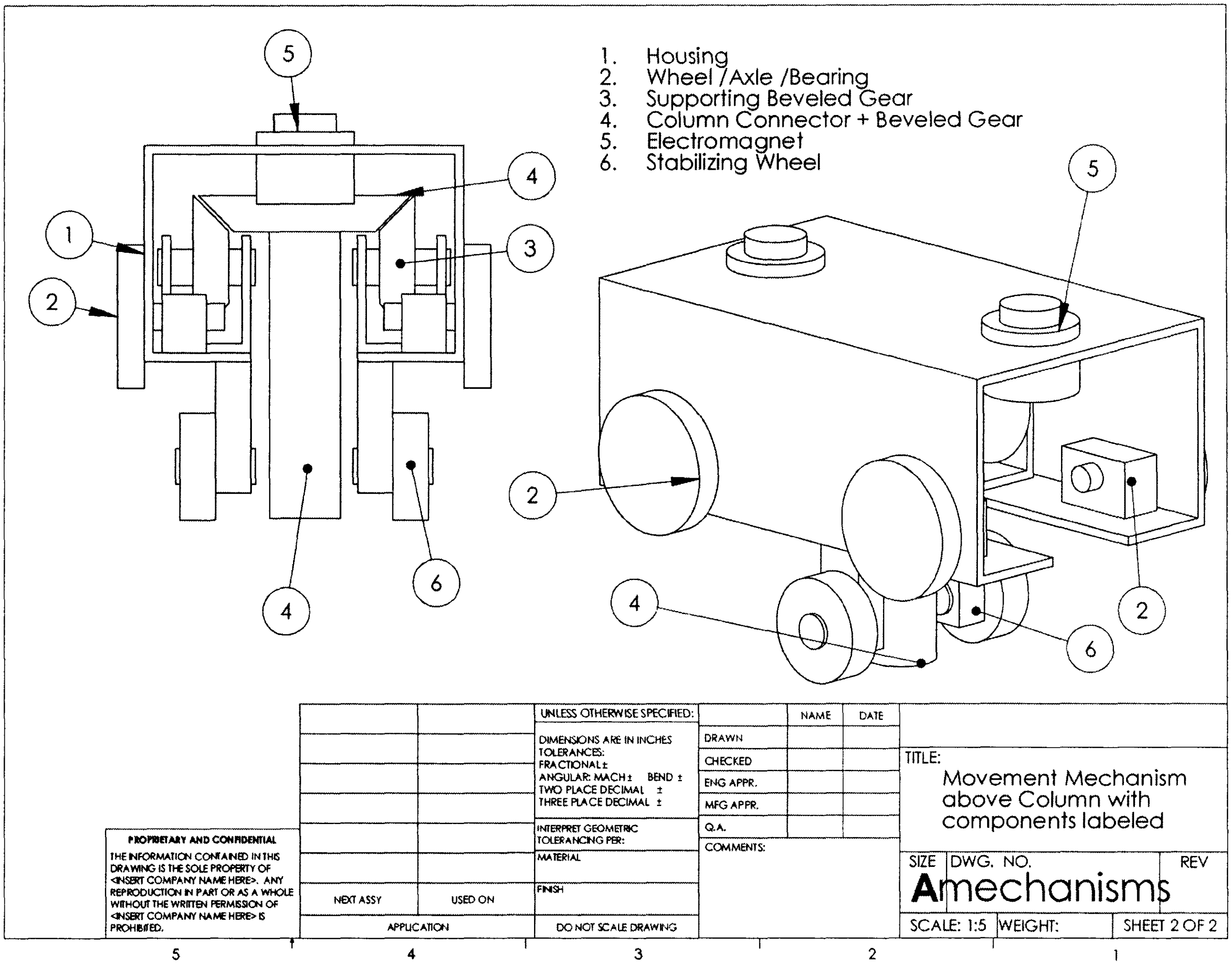
1. Housing
2. Wheel /Axle /Bearing
3. Supporting Beveled Gear
4. Column Connector + Beveled Gear
5. Electromagnet
6. Stabilizing Wheel
1
2
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DIMENSIONS ARE IN INCHES
TOLERANCES:
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INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
Movement Mechanism above Column with components labeled
SIZE
DWG. NO.
REV
A
mechanisms
SCALE: 1:5
WEIGHT:
SHEET 2 OF 2
5
4
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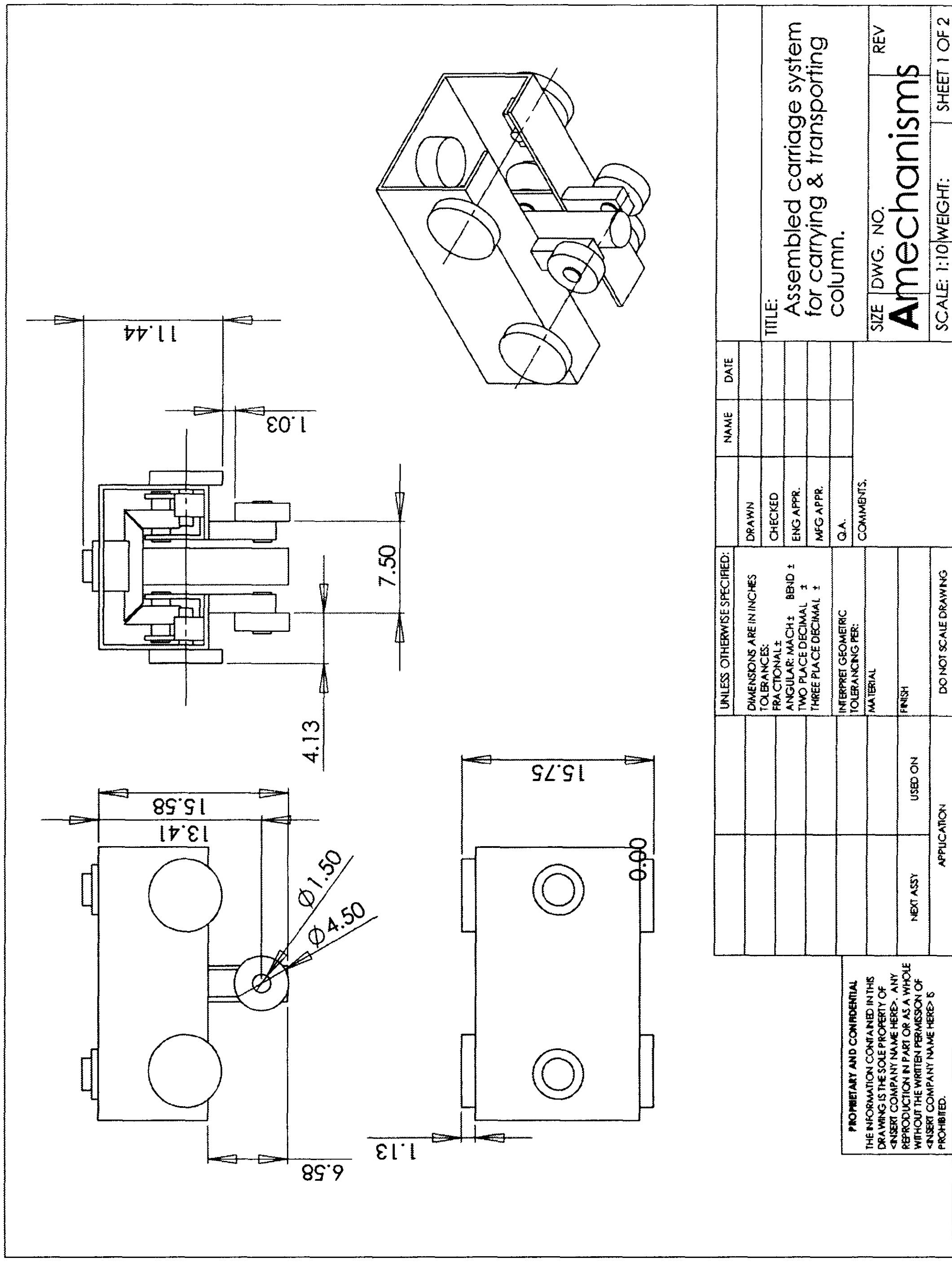

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1.03
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13.41
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Ø4.50
15.75
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USED ON
APPLICATION
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CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
TITLE:
Assembled carriage system for carrying & transporting column.
SIZE
A
DWG. NO.
mechanisms
REV
SCALE: 1:10
WEIGHT:
SHEET 1 OF 2
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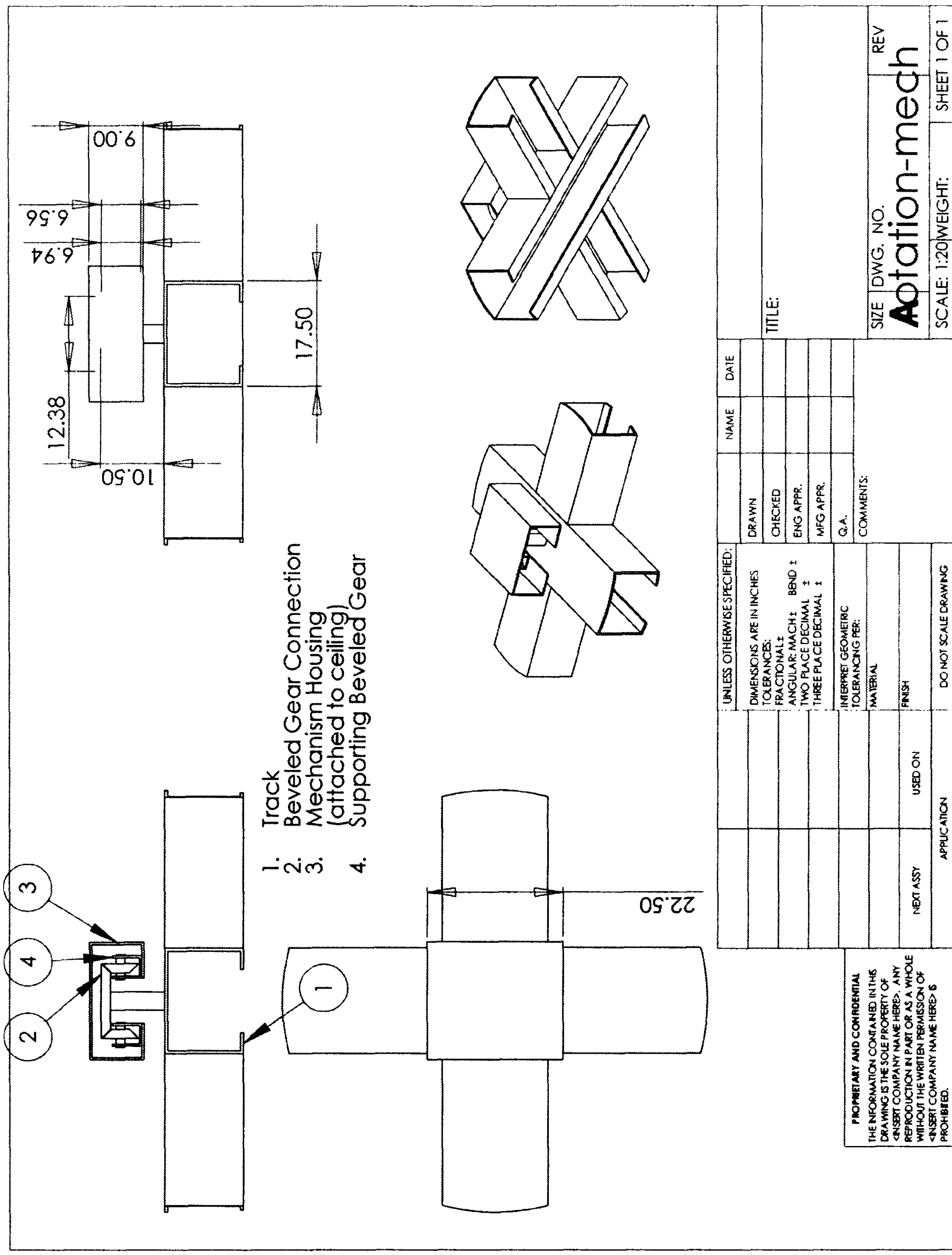
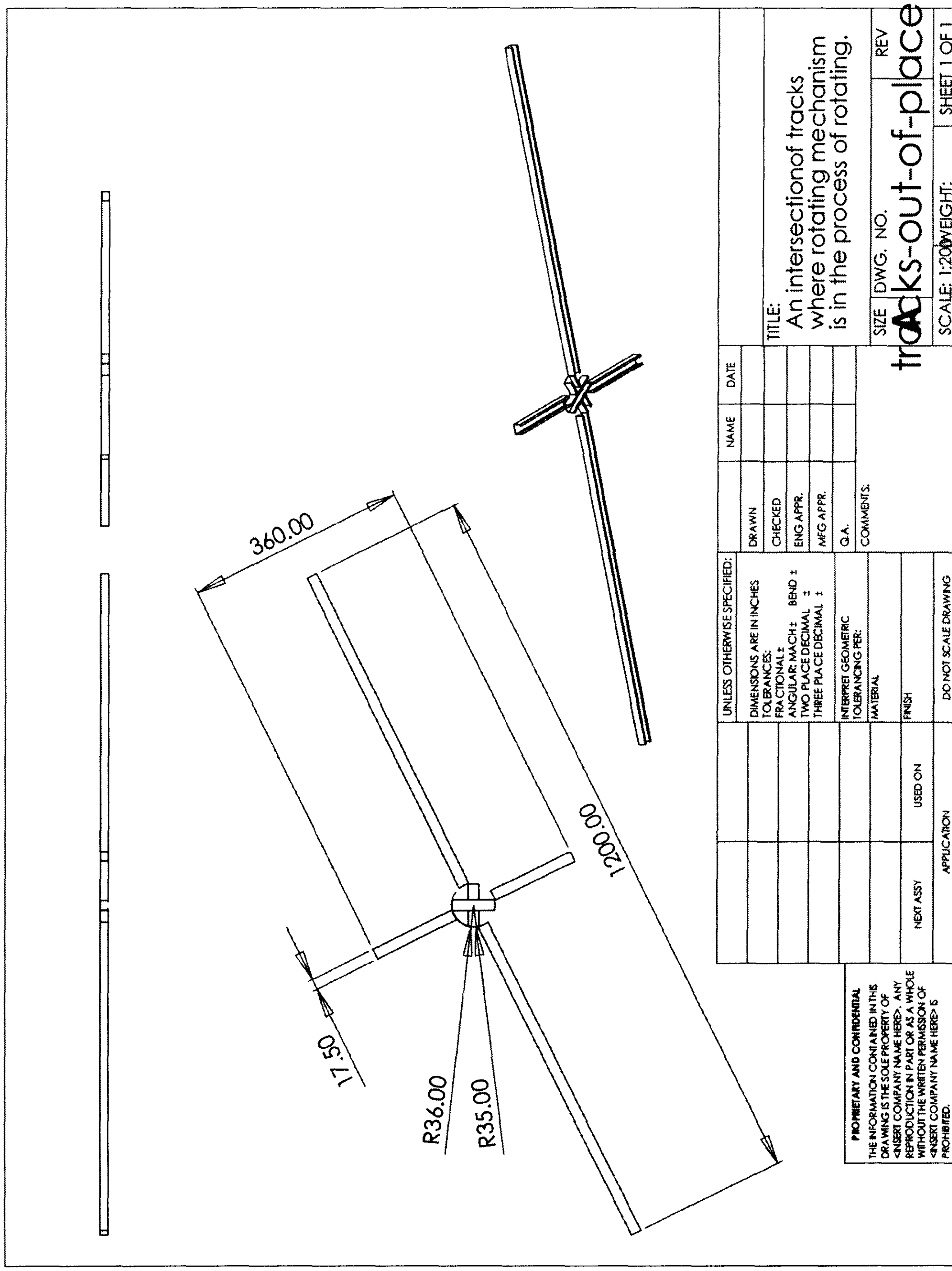
Appendix B: Track Mechanisms Drawings





360.00
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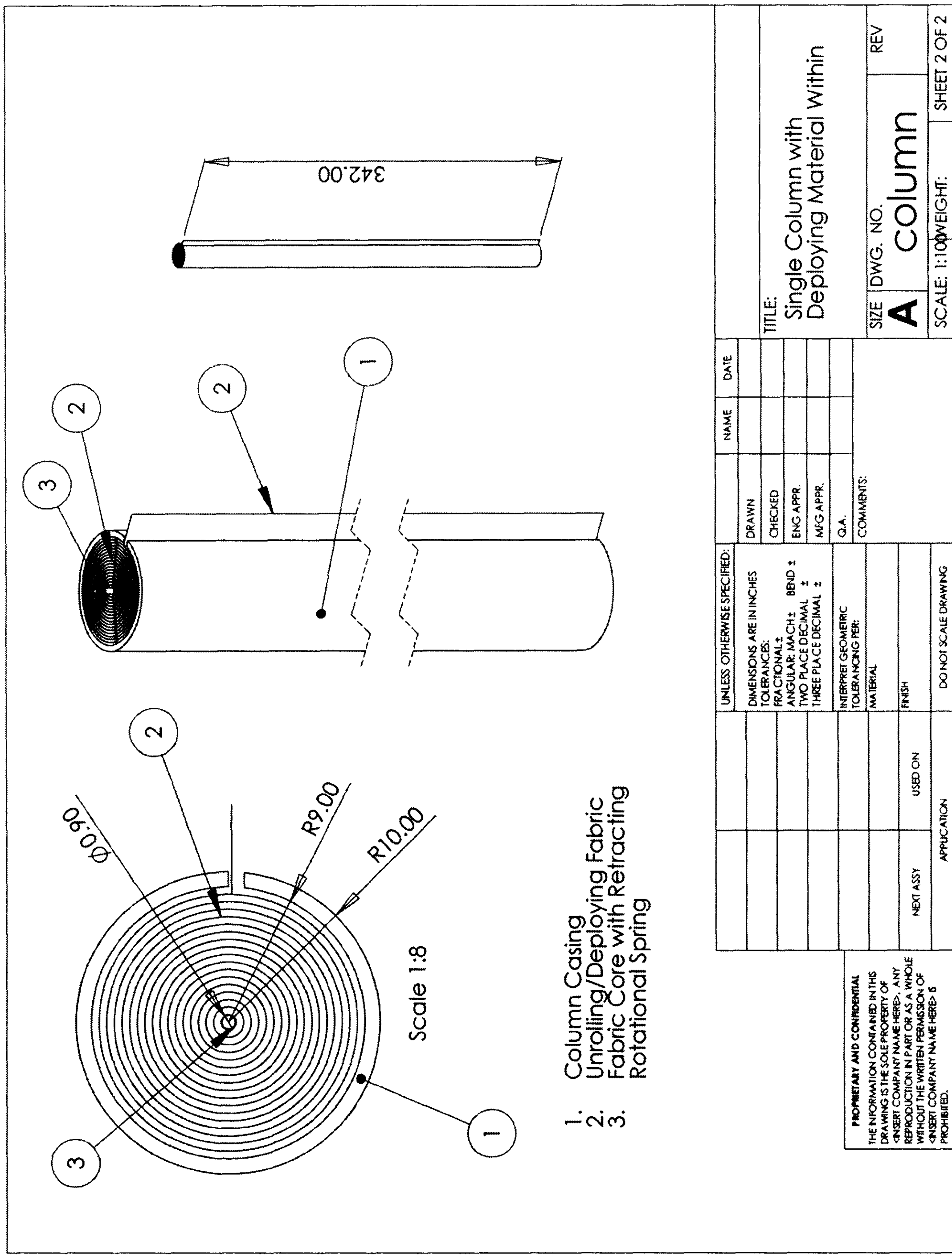
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
An intersectionof tracks where rotating mechanism is in the process of rotating.
SIZE
A
DWG. NO.
tracks-out-of-place
REV
SCALE: 1:200
WEIGHT:
SHEET 1 OF 1

<u>**Appendix C: Column Components Drawings**</u>



Appendix D: Fractal Geometries Background

It is Professor Frenchman's sense that fractal geometries will provide a promising starting point for the iterations of potential system designs. Carl Bovill aptly defined fractal geometry as "the study of mathematical shapes that display a cascade of never-ending, self-similar, meandering detail as one observes them more closely."[90] Fractal geometries often occur in nature. For example, the Barnsley Fern displays a fractal geometry as a branch of the fern is composed of smaller scale branches of the same geometry (Figure 42).[91] Another potentially important aspect of fractal geometries is how they can be constructed through the repeated smaller and smaller scale fragmentation of its parts. Examples include the Sirpinski Gasket, the Koch curve and the Minkowski curve, which grow to infinite length with infinite iterations (Figure 43). While the study of fractals goes far beyond this description, the extent that this system will mimic and draw from fractals will be limited to only several iterations of the self-same geometries in decreasing scales of operation.

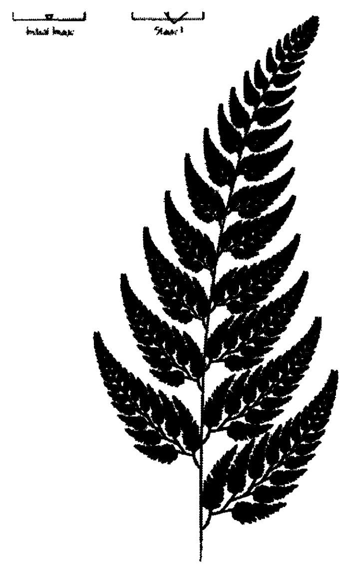


Figure 42. Barnsley Leaf[92]

[90] Bovill, Carl (1996). Fractal Geometry in Architecture and Design. Boston, Birkäuser.
[91] Ibid.
[92] Bovill, Carl (1996). Barnsley Leaf. Fractal Geometry in Architecture and Design. Boston, Birkhäuser.

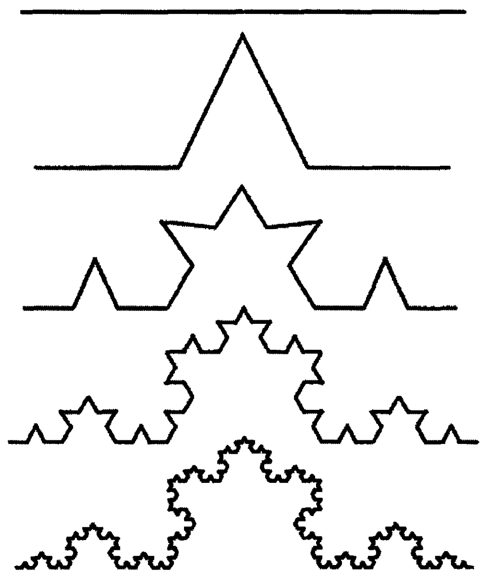


Figure 43. Koch Curve[93]

[93] Bovill, Carl (1996). Koch Curve. Fractal Geometry in Architecture and Design. Boston, Birkhäuser.

Appendix E: Planning and Architectural Methodology

This project is divided into three stages: investigation of the problem and program definition; architectural design; and mechanical design. Investigation of the problem or architectural program is essentially defining what types of uses and activities that the building-edge will need to support. Architectural design outlines what general form the building-edge should take to meet needs of the architectural program. Mechanical design focuses on how to build the architectural design, including the construction materials and the mechanisms that will allow movement and reprogramming of the system.

First, performance criteria are defined; these criteria include supportable activities and characteristics of the transformable edge. Activities may include museum exhibits, outdoor cafes, marketplaces or workshop spaces. Through selecting the specific activities and their associated space requirements to address in this project, the problem and architectural program are defined. Subsequent architectural and mechanical designs will be evaluated against this architectural program, or in other words, these performance specifications. In addition to supportable activities, when defined, these specifications will also include environmental standards that the edge should achieve, such as degree of weather tightness, conditioning, security, and lighting. Another important aspect of the performance criteria is the usability of the new building-edge such as whether the edge is easily reprogrammable or degree of morphological change possible.

Secondly, potential designs are created and various existing kinetic typologies are applied to the designs; the resulting designs are studied and evaluated based on the design criteria to determine which approaches are most promising.[94] Third, a detailed mechanical design is developed. Through these studies, a set of design and performance criteria and functional programmatic requirements are developed for use in the project. Once these design criteria are established, models of the museum edge are produced for each design in order to evaluate which design best achieves the set criteria.

The starting point for the architectural design investigations is an exploration of fractal geometries and the possible combinations and arrangements of doors in those geometries. Fractal geometries are relevant as they provide a systematically changing geometry, a characteristic that may allow for orderly reconfigurations. These configurations may aid in maximizing the usefulness of the space. The core element of fractal geometries are geometric shapes and variations in size of similar shapes. Thus, this portion of the exploration will involve systematically developing designs by changing shapes, the arrangement of shapes and their sizes. I will then go on to investigate other typologies of reprogrammable edges to see if they are combinations which offer potential. These typologies will include sliding and deployable elements. For both steps, developing diagrams and computer models of these designs will be integral to the investigative process. A visual representation of each potential form will facilitate an understanding of each system's capabilities and its advantages and disadvantages. The different forms yielded from each of these explorations will be assessed against the performance criteria and program, and will be narrowed to those that

[94] The form research will be conducted in a separate thesis for the Department of Urban Studies and Planning. That thesis will begin with case studies of existing examples of reprogrammable spaces and elements of architecture.

best meet the criteria. The most promising approaches will be investigated in more detail, including their mechanical design.

Through evaluating designs against the set of functional and performance requirements, the best architectural form will emerge, setting the stage for the research of the mechanical elements of the system.

The mechanical engineering research investigates the kinetic typologies and materials that this responsive environment requires, and in this way, this thesis also articulates a design methodology for kinetic architecture. Through looking at relevant examples of other types of kinetic and portable architecture and deployable structures, a toolkit is developed containing mechanical and architectural elements that can be used as portions of the kinetic system. By using this toolkit as a starting point, the mechanics and architecture evolve and take their own form.

Next, design of the mechanical system will respond to the functional requirements through the materials selection process and design of necessary mechanisms for movement. 3D computer modeling will also aid the understanding of the kinematics of the proposed solutions. Ultimately, this project consists of two parallel design tracks at different scales: the macroscopic scale of the building and the mesoscopic scale of the individual components that comprise the kinetic system.

Performance Specifications

Performance specifications for this new building-edge will emerge from an investigation of the problem and program definition. First, this thesis will explain what this changeable edge can achieve that a static edge cannot. Then, this investigation will seek to define the set of activities that this building-edge ought to support. The amalgam of supportable activities for this building-edge is a critical component of the program definition. Through identifying the specific activities that ought to be possible in this space, this thesis will also associate a particular configuration of kinetic elements necessary for each activity. Next in the development of the performance specifications, this thesis will set the environmental standards to be attained; examples include standards for: weather-tightness, security, or climate-control. Finally, the last performance criteria are those that define the measures of usability.

Architectural Design

The architectural design is the larger scale design that explores the overall form of the system. This process will require consideration of the performance specifications. These performance criteria will become the standard against which architectural design ideas are tested. Through this evaluation process, the design ideas will be narrowed to one or two promising ideas for more detailed design work. Further design will include the mechanical engineering design, which will help to ascertain if the design can actually work.

Through the investigation of precedents and the purpose of this reprogrammable space, a set of performance criteria will be developed. Precedents will provide a knowledge base of possible elements and kinetic typologies that may be useful to the new building edge. The architectural design will evolve by borrowing elements from these existing examples and their underlying concepts, adapting them to the performance needs. These performance criteria will include the activities that ought to be supportable within this building edge, the environmental standards of the kinetic structures, and the usability of the space. Establishing these criteria will be an integral step in the process of design; the criteria will serve as a means to evaluate the quality of proposed design ideas. The assessment process will narrow the options so that the subsequent mechanical design investigation can focus on the most promising designs. Thus, only after these criteria are established, can research into the architectural forms proceed, beginning with fractal geometries.

Fractal geometries will be used as an base map over which a system of armature can be laid to obtain a variety of configurations. The exploration of fractal geometries requires the selection of geometries with potential configurations that can meet the performance specifications. This weeding process can only occur through a systematic exploration of arrangements that movable partitions can sustain and through assessing how well these arrangements meet the performance criteria. A fractal geometry provides a starting point for organizing an open space, serving as a plan view skeleton over which new partitioning elements can be laid and reconfigured. In addition, these geometries allow the design of space to break free from the standard ninety degree room corner, to explore the advantages and disadvantages of other shapes for organizing space for use.

In the exploration of fractal geometries, the designs must be accompanied by considerations with how the arrangements can be achieved physically. Precedents become very important to this aspect of the design; the various kinetic typologies found in precedents—of which examples include different sized hinged doors, storage elements for deployable structures, or freely moving components—provide a library or toolbox to draw on for elements to verify the constructability of an architectural idea. These typologies are applied to the fractal-based system to define the system in the third dimension through specifying the form of the spatial dividers.

3D computer modeling will allow each design to be evaluated for its visual and functional impact. Through the systematic exploration described above, a set of potential designs ideas will emerge. 3D modeling will provide a better sense of how the system will physically appear, thus serving as a tool for evaluating its visual impact and usability. In addition, the virtual modeling will allow elements to be easily shifted around the space into different configurations to explore the effectiveness of potential movements and structures as well as to simulate the reprogramming of the system.

Once the architectural design ideas have been assessed and the one or two best ideas have been selected, the mechanical design of the system can begin. Following the investigation of mechanical design, the project will return to a second stage of assessing the proposed architectural forms, but this time with attention to the mechanical feasibility and cost of construction. At this point, the final architectural form will be selected, and the project can enter the final stage of mechanical design in which the mechanisms for the best architectural forms are selected and designed with even greater detail.

Appendix F: Performance Specifications

Museum of the Mile

The museum for which is building-edge is being designed is called "The Museum of the Mile," created specifically for The Digital Mile. This museum will engage children and their families with technology and thus provide a positive experience with technology. This museum will both be a collection of information from The Digital Mile environment as well as a control center for programmable elements of the Mile. The Mile will be visible at the museum where information about the Mile is collected and displayed. This display may be something like the "iSpots" project at MIT, a project that creates a real-time display of level wireless internet usage at each of the 2,800 access points on the MIT campus.[95] At the Museum of the Mile, this sort of data collection may be a similar study of wireless uses, or even a display of people's paths of movement through the park. As a control center for the Miles, this museum will offer visitors the opportunity to manipulate the programmable elements of the mile, thus digitally controlling the program of the environment.

Supportable Activities

The selection of supportable activities depends on the purpose of the space as part of the Museum of The Mile. This space may function as a part of the museum as a place for outdoor museum exhibits or as a place to display real-time digital images of park usage. This space may also function as a place separate from the museum, much like a plaza or arcade in front of a building providing open seating or space for a street market. This diversity of supportable activities is what distinguishes the reprogrammable edge from a static building-edge.

This section will define the various space configurations that the building-edge out to be able to form to support a desired set of activities. To do so, this section will present a set of wall arrangements and the possible activities that can occur within these arrangements. Through defining these configuration demands and their associated activities, this thesis will explore the extent of the problem which includes necessary building-edge capabilities, and in addition, the architectural program of the building-edge will be defined.

There are six basic edge configurations that may potentially be feasible with this rearrangeable system: a straight edge (line), an open edge, a serrated edge, stalls, modules, and free forms.

1. Line: The straight-line edge allows the building to be sealed, creating an exterior wall like any other building, and thus, limiting access to the interior of the building (Figure 44).

[95] "iSPOTS: How Wireless Technology Is Changing Life on the MIT Campus." Retrieved March 19, 2006, from http://ispots.mit.edu.

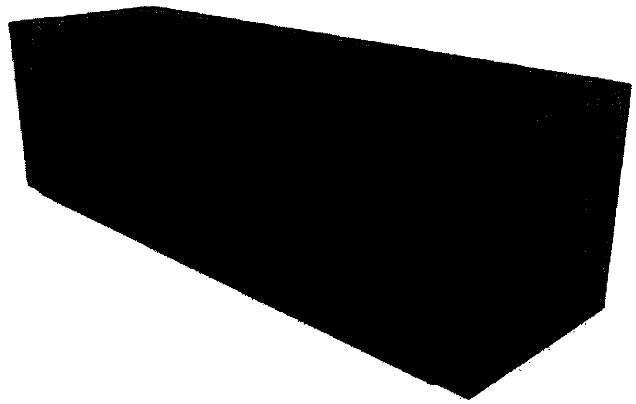


Figure 44. Flat, "Line" Edge

As part of the Museum of the Mile, such a sealable edge is integral to its function as a museum. Any museum is a museum because it contains a collection of elements of some value that cannot be viewed elsewhere; this inherent value of the museum's contents necessitates a way to secure the space and protect its contents. This secure edge may be necessary for night-time hours or special exhibits which require security measures such as metal detectors and a controlled flow of visitors in and out of the space. This edge need not only be on the exterior edge, but may occur at the back of the edge-space.

2. Open: The open edge allows the building-edge to open up for unimpeded visual and physical access to the interior of the museum (Figure 45).

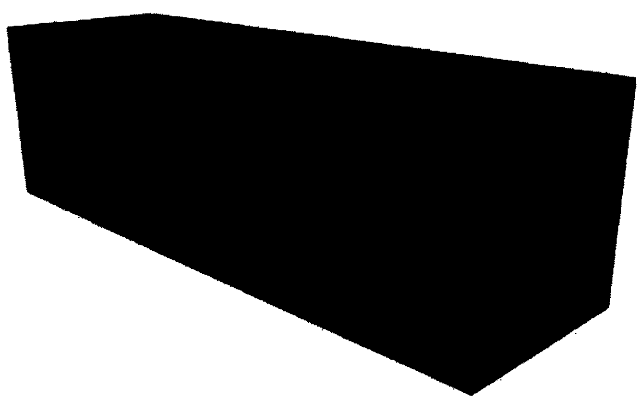


Figure 45. Open Edge Model

While still providing display space, this configuration allows open-air free access that will be important to the Museum of the Mile. Physical and visual open access to museum galleries supports the symbolic role of the building-edge and museum in The Digital Mile, a place unified by open access to information.

Movable elements may also permit the building-edge to become an open-space allowing for large events or community gatherings. Performances can make use of wide open spaces as this large 30 feet by 100 feet space would undoubtedly have enough space for an audience even after a stage is brought in. Community meetings can also make use of such a large space for presentations, town-hall type meetings, or large celebrations. Large open spaces can also contain tables and seating areas for people to loiter in a partially enclosed area while visiting The Digital Mile. These seating areas can also support a café on the edge of this space or just outside this space, within the museum interior spaces. The major limitation of a café would be the infrastructure necessary to support a venue that requires constant running water and electricity; accommodating those needs may be difficult if the moving elements interfere with the space. Thus, the recommendation that café remain at either the edge of the rearrangeable space or just outside the space.

3. Stalls: A configuration that permits a series of stalls, or partitioned spaces with one open edge, allows for distinct uses to occur simultaneously without directly interfering with one another while still allowing free access to visitors. These stalls may open towards the exterior or the interior of the museum (Figure 46).

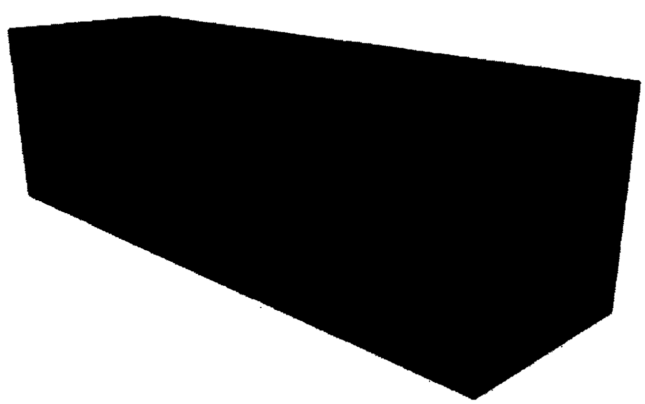


Figure 46. Stalls Configuration Model

This configuration can create separate stalls for individual vendors or sections for various groupings of merchandise. For example, these stalls may provide visual separation between gift shop merchandise and street food vendors. These booths may face indoors or outdoors, or even both simultaneously. Outdoors spaces will be more conducive to markets and activities that are not as relevant to the museum; these activities may include stalls for an ethnic festival or a community flea-market. Indoor spaces can relate to interior exhibits, creating space for educational activities for museum visitors. This building-edge may also be able to support a marketplace with different vendors or different groupings of merchandise. These markets can be based on the idea of a transient market, much like a flea market where vendors sell goods over a folding table. Another variation would be a marketplace much like Boston's weekly Haymarket (Figure 47).

Figure 47. An makeshift stand at the weekly Boston Haymarket.

5. Serrated: The serrated edge is similar to the stalls configuration, but unlike the stalls, the partitioned spaces face different directions (Figure 48).

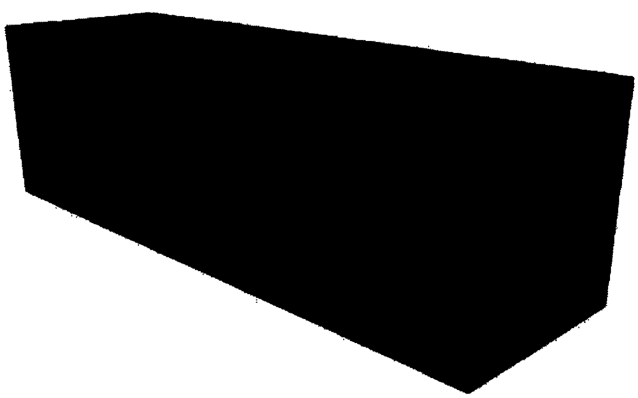


Figure 48. Serrated Edge Model

This configuration creates the potential for exhibit spaces that protrude out of the building while still maintaining a weather barrier between the exhibit and the outside. Assuming these partitions are of transparent materials, such a configuration allows displays to be viewed from the exterior while still providing enclaves for activities supportable by stalls as described previously.

4. Modules: The configuration that creates enclosures, or closed shapes that can be used as distinct, bounded spaces (Figure 49).

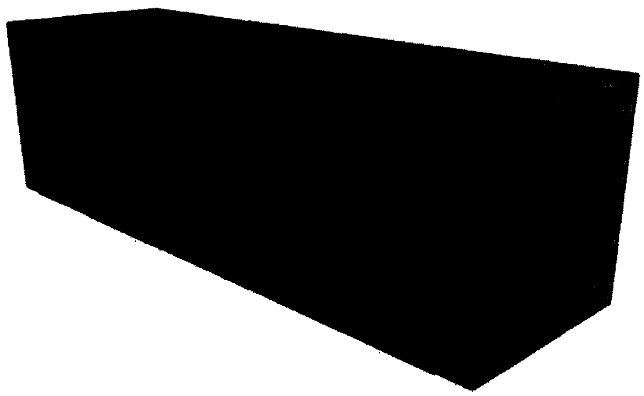


Figure 49. Enclosed Edge Model

As the Museum of the Mile serves as an educational tool for children and their families, classroom space may also be an important function of this rearrangeable building-edge. Classroom space can be created by making enclosed spaces; enclosed spaces are important for limiting outside distractions and for teaching children without the constant fear of someone disappearing. A sample of other activities that may make use of enclosed spaces include small group meetings, temporary workshops and distinct museum exhibits. Outside these enclosed spaces, visitors can continue to experience the open exhibits or open access to interior museum spaces.

An ability to create closed rooms may provide space for workshops or office spaces in this museum. While the idea of enclosed spaces is one that this thesis will pursue, likely these uses will not be the aim. Unlike exhibits or projections, these uses are not as transient and generally require more permanence. Workshops often must be maintained over a period of a project, which limits the flexibility of the space and would probably be better served by a permanent workshop space. The same reasoning applies to office space.

5. Free Forms: Free form configurations will be configurations as the name implies. For this configuration, the walls can be placed without pattern, or in patterns that are not predefined (Figure 50).

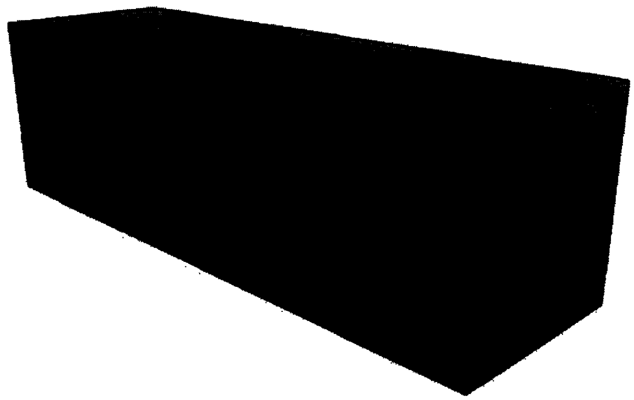
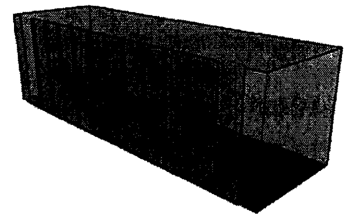
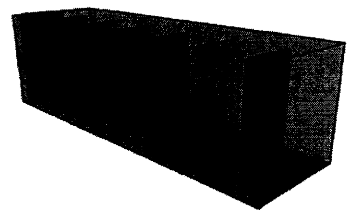
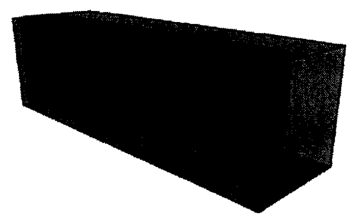
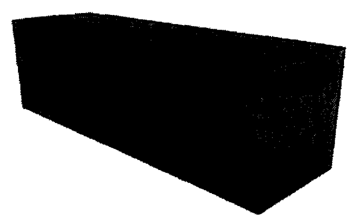
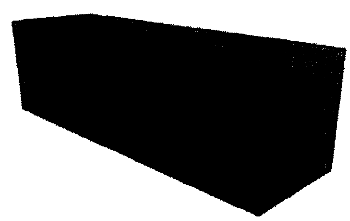
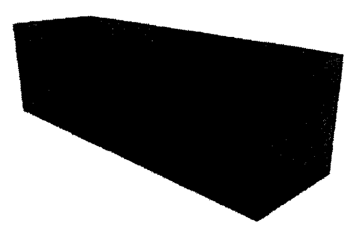


Figure 50. Free Form Edge Model

This space may an extremely flexible temporary exhibit space, allowing curators to modify even the locations of the display surfaces and exhibit containing spaces. The space partitions can be arranged by a curator to guide visitors in a specific path through the different displays to convey a particular message. In addition, the curator may vary the openness of each section of the exhibit from partially open spaces to closed rooms, or even a mixture of both as the partitioning elements can be moved around based on the demands. These spaces may provide a mixture of stalls, enclosed spaces, and serrated edges. Beyond museum exhibits, these walls can also optimize the usefulness of the space by combining a variety of uses within the distinct configurations that can be created simultaneously. This flexibility of the partitioning elements sets the reprogrammable building-edge apart from the standard static edge.

Table 13: Summary Table of Basic Edge Conditions

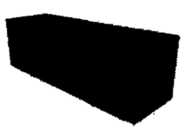
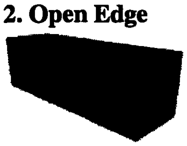
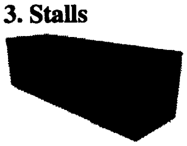
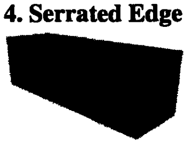
Form Name	Measure of Success for Evaluation	Diagram
1. Line/Sealed Edge	Can this edge be completely sealed?	
2. Open Edge	Does this edge offer complete physical and visual access to interior?	
3. Stalls	Does this edge provide sufficient separation for simultaneous independent activities?	
4. Serrated Edge	Does this edge provide sufficient enclaves for activities on both the interior and exterior?	
5. Enclosed Edge/Modules	Does this edge create completely enclosed spaces where independent activities can occur without outside distractions?	
6. Free Form Edges	How well can this edge create shapes that are not part of the initial set of pre-defined configurations?	

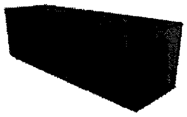
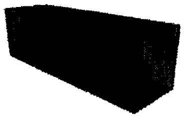
In addition to the physical forms that ought to be arrangeable by this kinetic system, an important aspect of the supportable activities is the activities that are made possible by the characteristics of the walls themselves. These activities that add another level of flexibility to this new building-edge involve the display of material on the walls and the changeability of the visual properties of the wall material.

This new building-edge ought to be able to display educational material, both as a place to post physical exhibits and a place capable of carrying digital projections or images. The ability to carry digital projections or changing images on the walls of the kinetic architecture increases the flexibility of the space by incorporating visual flexibility with physical flexibility. As a place to post exhibit material, there is also some level of visual flexibility with each new exhibit, although not as much as a digital projection. Another aspect of visual flexibility involves the quality of the space partitioning surfaces. As explored in the materials section, there are types of glass that can be actuated to change opacity and color, a characteristic which can subtly change the atmosphere of the space.

While each of the functions addressed above are individually achievable by static building-edges, the new reprogrammable building-edge will provide a combination of these uses and configurations. In this way, this new edge serves a wider range of activities and groups simultaneously and at different times, optimizing the usefulness of a single space. These performance specifications of open access, stalls, and complete openness are elements that ought to be present in any design proposal to support the widest variety of activities.

Table 14: Summary Table of Performance Specifications and Evaluation Criteria

Performance Specification	Measure of Success for Evaluation	Relevance
	FORM	
1. Line/Sealed Edge 	Can this edge be completely sealed?	Architectural Design
2. Open Edge 	Does this edge offer complete physical and visual access to interior?	Architectural Design
3. Stalls 	Does this edge provide sufficient separation for simultaneous independent activities?	Architectural Design
4. Serrated Edge 	Does this edge provide sufficient enclaves for activities on both the interior and exterior?	Architectural Design
5. Enclosed	Does this edge create completely enclosed spaces where	Architectural

Edge/Modules 	independent activities can occur without outside distractions?	Design
6. Free Form Edges 	How well can this edge create shapes that are not part of the initial set of pre-defined configurations?	Architectural Design
7. Wall Surface	Can the wall surface carry digital projections? Is the surface programmable? Changeable? How flexible is the wall surface/wall material?	Mechanical Design: Materials Selection
	ENVIRONMENTAL STANDARDS	
Exterior Standards		
1. Weather-Tightness	Does the exterior edge shield the interior from outdoor weather conditions? Provide shelter for visitors and protect exhibit materials?	Mechanical Design: Materials Selection
2. Security	Does the exterior edge have strongly fixed kinetic elements to secure the museum's valuables? Is the material sufficiently impenetrable?	Mechanical Design
3. Corrosion Resistance	Is the exterior material corrosion resistant?	Materials Selection
4. UV Radiation Resistance	Is the exterior material UV radiation resistant?	Materials Selection
5. Non-flammability	Is the exterior material non-flammable to prevent the spread of an outside fire into the museum?	Materials Selection
Interior Standards		
1. Lighting	Can light pass through the walls? Can each area of the space be lit at all times?	Mechanical Design
2. Provision of Shade	Does the interior space provide refuge from direct sunlight?	Architectural Design
3. Air Conditioning	Does the interior/exterior edge have sufficient air-tightness for cooling and heating interior space with air-conditioning?	Mechanical Design
4. Electricity	Does this setup provide room for electric wiring to power the automated reconfiguration of the space?	Mechanical Design
	USAGE	
1. Programmability	How many distinct configurations are possible?	Architectural Design
2. Flexibility	Can this system create configurations outside the pre-determined and pre-set configurations?	Mechanical / Architectural Design
3. Reconfiguration Ease	How easily is this system set up and rearranged? Is the system computer-controlled? Motor-actuated?	Mechanical Design
4. Speed	How much time is necessary for the system to reconfigure? Is the time long?	Mechanical Design
5. User Characteristics	Who is capable of reconfiguring this system? Does it require training or can anyone adjust the building-edge configuration?	Mechanical Design

Appendix G: Architectural Design

Design Exploration

This section will articulate the design process that was used to arrive at various architectural designs and their associated reconfiguration capabilities and space arrangements. Each idea evolves from a basic concept that built upon with different levels of complexity and variation. The first starting point is the concept of fractals that was proposed by Professor Frenchman. This base concept yields two categories of forms: one where armature is manipulated along a fractal pattern and another where armature is arranged in a fractal pattern. The third and last series of forms is a synthesis of the potential flexibility presented by the prior series and an attempt to create a system that is capable of realizing numerous ideas simultaneously for a truly moldable space.

Following each series of potential arrangements, this section will also provide a brief discussion of the mechanics of each architectural system. The aim of these discussions is to ensure that the architectural design is mechanically feasible, or that potential methods of construction exist prior to proceeding with further evaluation or design. If the structures and forms cannot be constructed, further exploration of their usefulness in urban design will be unnecessary.

I. Fractal Pathways

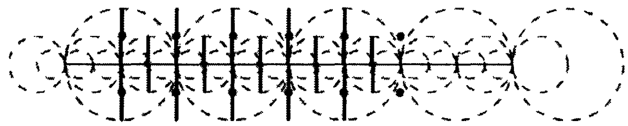
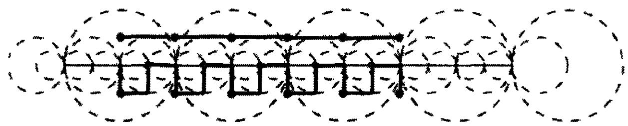
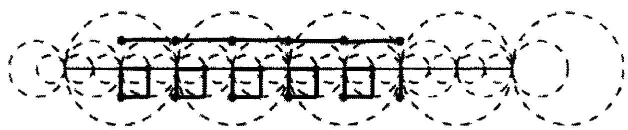
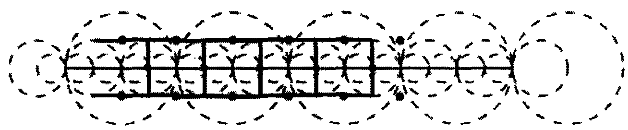
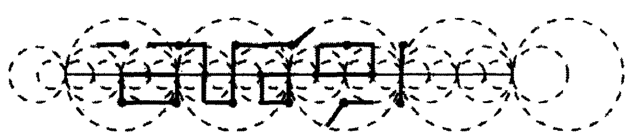
The architectural design developed based on movement of armature in a fractal pattern yields a series of potential designs and configurations. These configurations may or may not include fractals in the shapes that they create, but the guidance of the fractal patterns provides a systematic method of reorganization. Through defining pathways for movement, this hunch anticipates that the resulting configurations may be capable of obtaining the defined form specifications.

These designs involve hinged and sliding doors that move in ways such that their paths create fractal geometries. The model of hinged doors is based on the proposal by Professor Dennis Frenchman. The model with sliding walls is based on a mechanical concept observed while in the radiology department of the medical clinic at the Massachusetts Institute of Technology. Each design is based on a system movable walls of fixed-size; a set of hinged walls swing around a post while the sliding walls are moved around the space.

1. Hinged Doors

Using the diagrams created by Professor Frenchman in the following table, this model uses rotating hinged doors as the basis for rearrangement. The circular movement of the doors generates the fractal pathways; each of the red and blue dots represents a node at which two hinged doors are attached. Mechanically, the design of this system appears to be relatively simple: permanently fixed columns with hinged doors attached to the columns. The following diagrams demonstrate the ability of this system to achieve the six classes of edge conditions defined in the performance specifications section.

Table 15: Potential Hinged Door Configurations using Fractal Pathways[96]

Form	Diagram
1. Open Edge	
2. Line Edge & Serrated Edge	
3. Line Edge & Modular Edge	
4. Modular Edge	
5. Modular Edge & Stalls	
6. Free Form	

In this model, three sizes of circles are marked in dotted lines but only one size is used. The doors in this model swing on fixed paths with fixed sizes where each door creates a circular path of identical size. The drawback of such a system can be seen in the fifth potential configuration. The varied dimension of enclosure space in this orientation prevents the walls from meeting to fully seal the spaces. When the doors do not meet in a desired configuration, the mechanical design becomes complicated as they cannot be secured through locking to one another.

In order for the other pathways to be used, different sized doors are needed to create the larger and smaller arcs. Varying sizes of doors create yet another obstacle: in order for the doors to have complete rotation, pathways can only be tangential to one another. Consequently, a smaller circle cannot be embedded within another to create different layers of complexity for a true fractal geometry. Neither can pathways of the same size intersect; while physically possible, the movement of the doors becomes increasingly difficult as each door will then serve as an obstacle to the other.

2. Sliding Doors

[96] Frenchman, Dennis Fractal Pathways using Hinged Doors.

A way of increasing the flexibility and minimizing the disadvantages of doors with a fixed size is to allow the supporting columns to move around the space with the doors attached. A good precedent for moving large objects easily around large space is the kinetic technology used in the medical field. Medical equipment is designed to facilitate medical procedures of varying complexity, difficulty and precision and is often at the vanguard of technology because of its role in improving quality of life. The relevant kinetic technology observed MIT Medical's radiology department is the track system for moving the large x-ray machine (Figure 51).

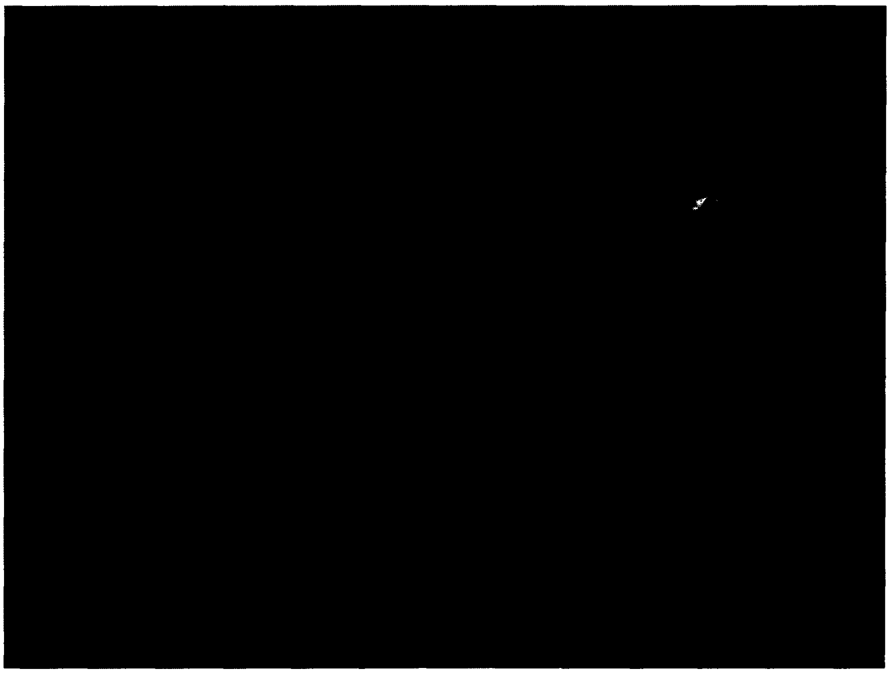


Figure 51. X-Ray Machinery on crossing tracks at MIT Medical

The crossing tracks are two sets of bearings. The x-ray machinery runs along one track set 1 in one direction. Track set 1 then moves along track set 2, thus creating allowing the x-ray machine to move in two independent directions. This allows the machine to move to virtually any position in the room. This setup demonstrates the mechanical feasibility of moving columns which may be comparable in weight to the x-ray machine.[97]

Through moving columns, the hinged doors acquire another level of flexibility and become sliding doors. The following hand drawings demonstrate potential configurations and reconfigurations using this concept of hinged doors on sliding bearings (Figure 52). Note these configurations use two columns to support each wall.

[97] This ability to move columns will also be important later in this thesis in the "Flexible Armature" section of the architectural design.

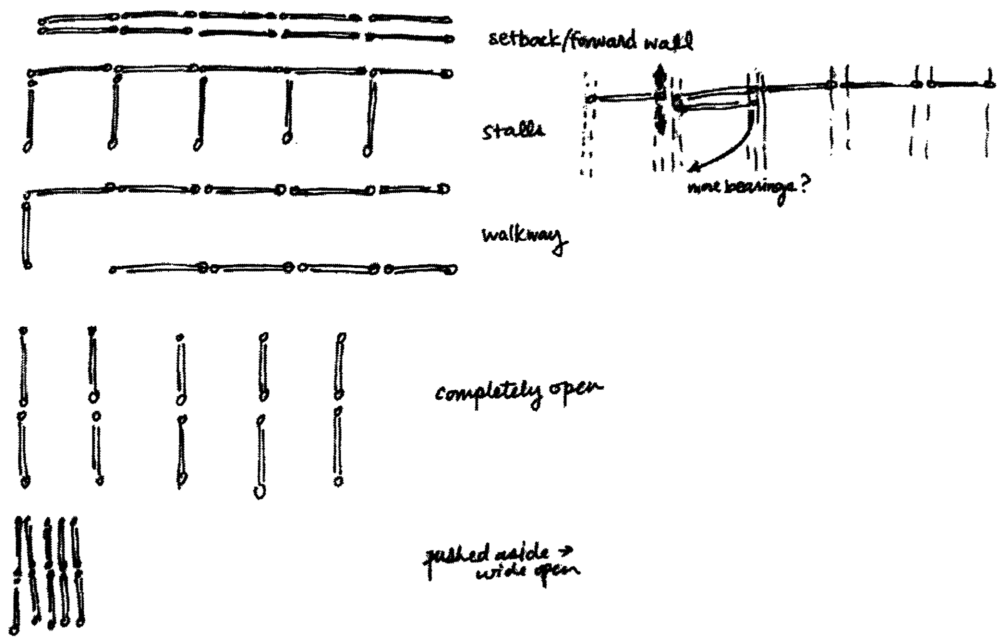


Figure 52. Potential Configurations for Doors on Sliding Bearings

The configurations above can be systematically achieved in the order above. These movements are dependent on rotation around the nodes drawn as circles and sliding of those nodes either forwards and backwards or side to side. The drawings achieve four of the six forms prescribed in the performance specifications section. Modular enclosures are possible, but the number of enclosures would be limited by the total number of walls. A free-form edge would also be possible, but orientation of the walls will be limited to the two drawn above that are 90 degrees apart.

The above configurations can also be achieved with a similar design but with only a single column for each wall. Stabilizing the wall will again be more difficult without two points firmly fixed to the ceiling or floor. Walls will also only be able to rotate around one end and not both as seen in the last figure.

Neither potential design of sliding doors actually maximizes the flexibility offered by the sliding tracks. The presence of two columns in the first design confines the orientation of the walls to two directions. The singular column in the second design, the free rotation of the walls is limited to one side of the wall, thus increasing the number of movements of walls to achieve the same physical result.

II. Fractal Arrangements

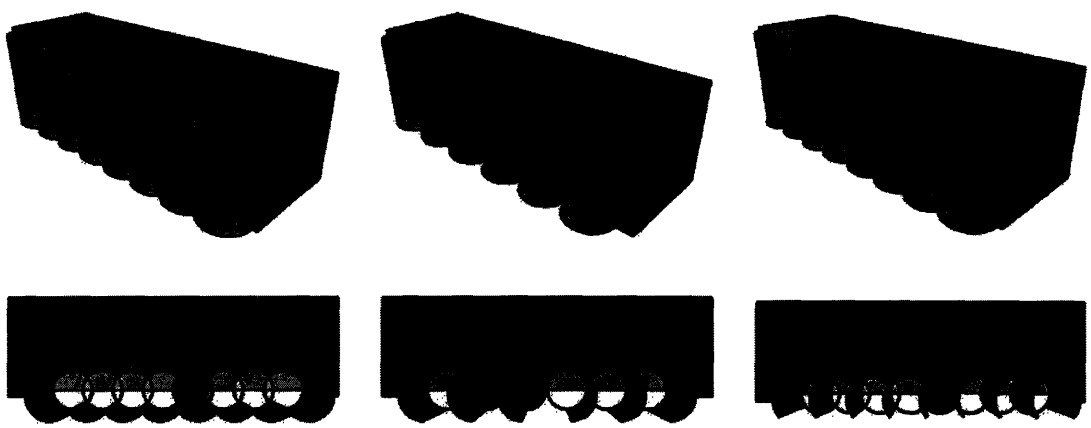
The underlying concept behind fractal geometries is the repetition of geometric elements regardless of their shape or orientation. The following series of forms use the armature to create these fractal geometries when viewed in plan, some simply articulating well-defined fractal geometries while other play on existing geometries, creating different layers of complexity by the arrangement of shapes and shapes of different sizes.

1. Circles

The first series of forms is based on the geometry of a circle. First, a variation of each of the forms defined in the performance specifications section is created. Then, using the concept of fractal geometries, different sized circles and layers of circles are used to develop other possible configurations. Each of these configurations is based on a mechanical design where the circular or semi-circular pieces travel on a circular bearing above and below. Each circular piece is constructed of several pieces which can be collapsed, similar to window blinds; this contractibility allows the circular walls to vary the length of the arc each wall segment creates.

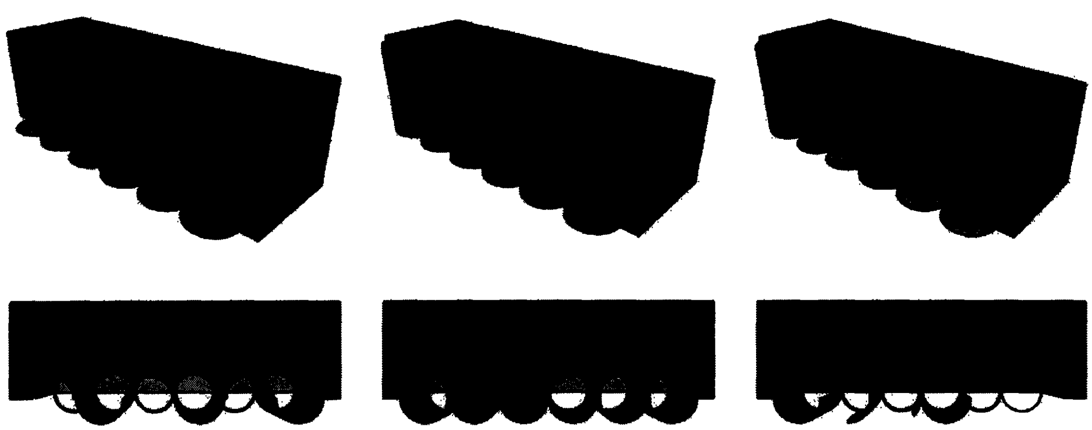
The following two tables demonstrate how a series of identically-sized, tangential circles can meet the edge conditions prescribed by the performance specifications.

Table 16: Edge Conditions 1-3, Identical Tangential Circles



Sealed (Line) Edge | **Open Edge** | **Stalls (Exterior)**

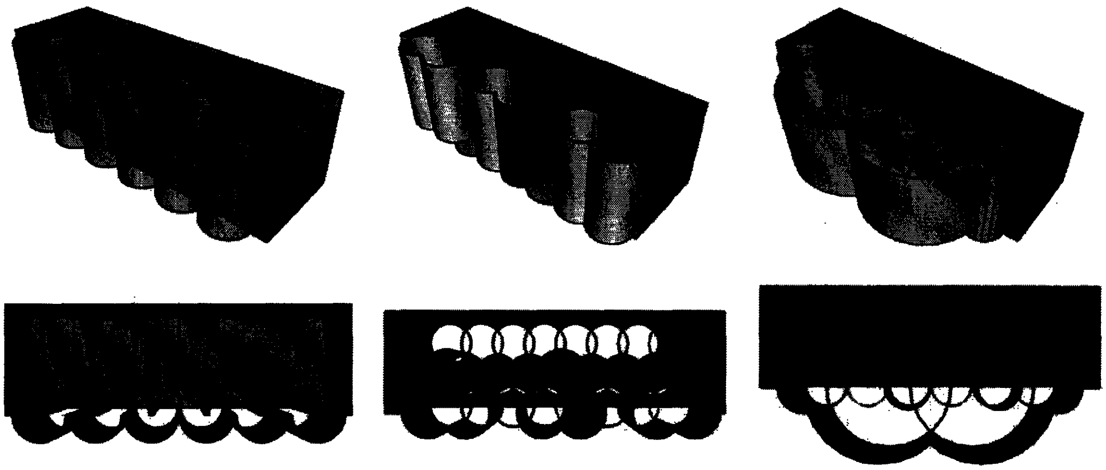
Table 17: Edge Conditions 4-6, Identical Tangential Circles



Serrated Edge | **Enclosures/Modules** | **Free-Forms**

The next two tables explore variations of circle arrangements. These configurations allow the circles to overlap, create multiple layers of circles and utilize a variety of sizes.

Table 18: Potential Configurations, Various Base Plans



Interior Walkway | **Clover Leaf Modules** | **Size Variation**

2. The Dragon Curve

The next series of fractal configurations uses the dragon curve to create a mixture of space-types. The dragon curve is created through using the original line segment as the hypotenuse of an isosceles right triangle and then eliminating the original segment (Figure 53).

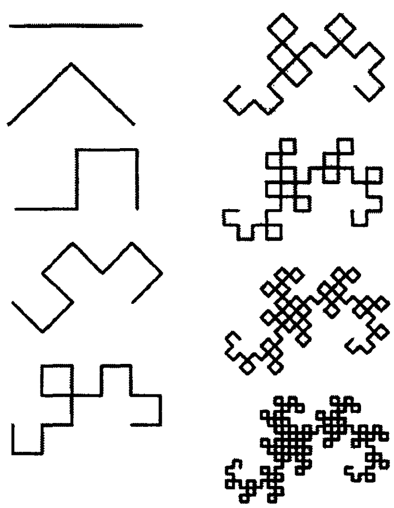
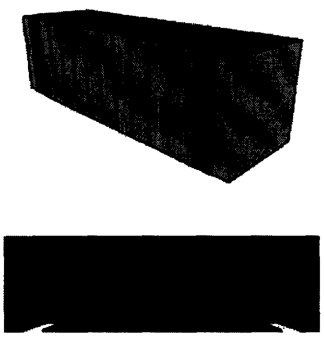


Figure 53. Dragon Curve Fractal Series[98]

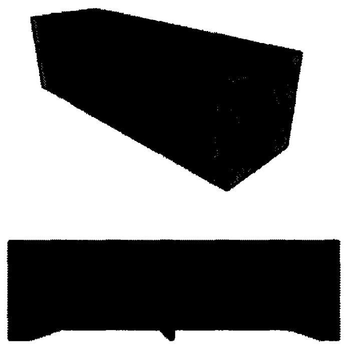
[98] Bovill, Carl (1996). Dragon Curve. Fractal Geometry in Architecture and Design. Boston, Birkhäuser.

Through this series, the complexity of the fragments increases with each iteration creating an increasing number of spatial configurations from partitioned space to stalls to enclosures. Because each segment is dependent on the segment before, this concept is based on the idea of an extending wall, growing longer with each layer of fragmentation. In other words, the material deploys between two starting points and is stretched to the new shape by the addition of another post to create the two legs of a new right triangle from the original segment that would have been its hypotenuse.

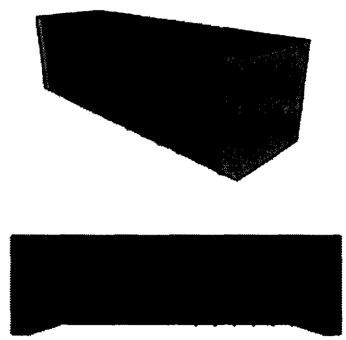
The flowing tables demonstrate the potential versatility of space when using a dragon curve as a method of programming the rearrangeable walls.



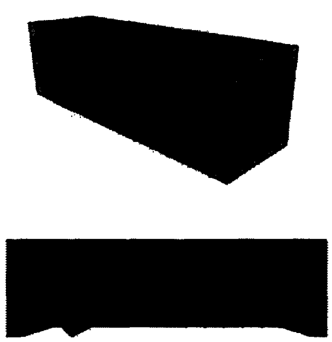
Dragon Curve, Flat



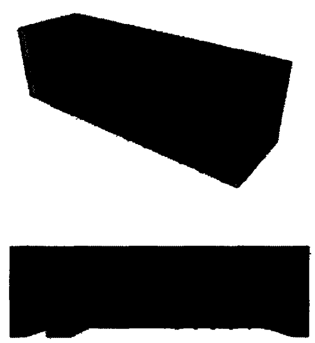
Dragon Curve, Level 1



Dragon Curve, Level 2



Dragon Curve, Level 3



Dragon Curve, Level 4

Unlike the configurations based on circles that can distinctly create each of the forms defined in the performance specifications, the configurations using the Dragon Curve creates a mixture of these forms in each configuration. The distinction between this series and that of the sliding walls and the circles is the ability to create a unique mixture of the pre-defined forms and for that mixture to occur at varying depths and sizes in the building-edge space. In addition, the dragon curve is a unique curve in that it intersects with itself without ever crossing itself regardless of the number of iterations;

this characteristic facilitates reconfiguration as any configuration based on this fractal can be constructed without intersecting walls.

3. The Sierpinski Gasket

This last series of fractal configurations uses the Sierpinski Gasket to position walls and create triangular spaces (Figure 54). This series uses the idea of the "cascade of never-ending, self-similar… detail" to create a variety of shapes and sizes of spaces.[99]

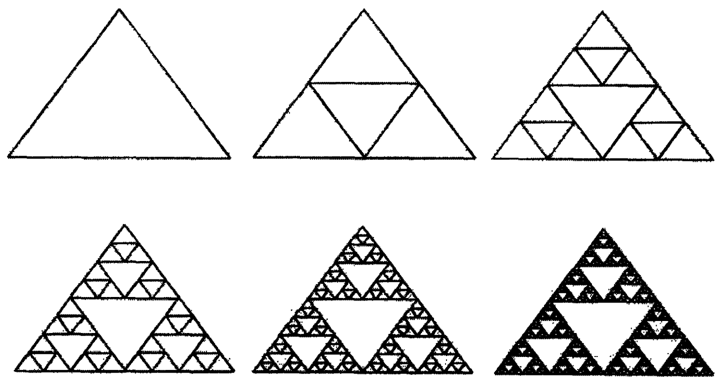
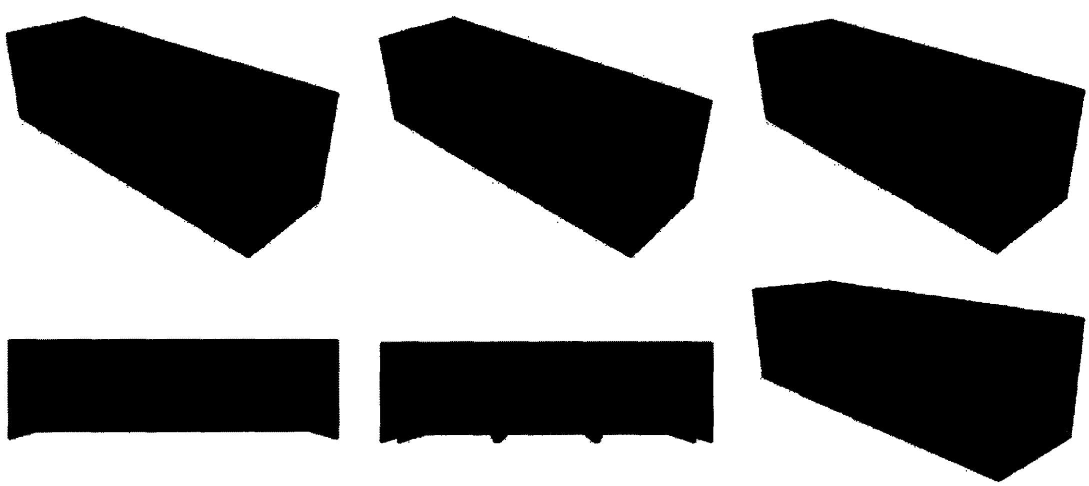


Figure 54. Sierpinski Gasket Fractal Series

The following two tables carries the Sierpinski Gasket through several iterations and demonstrates the types of spaces that would be created with this system.

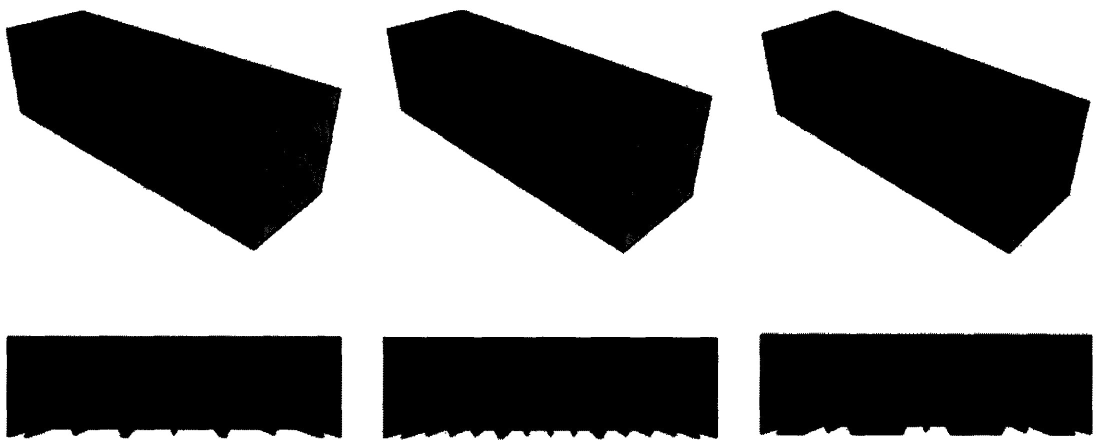
Table 19: Sierpinski Gasket, Basic Models



Sierpinski Gasket, Base Triangles	**Sierpinski Gasket, Level 1**	**Sierpinski Gasket, Level 1 Enclosures**

[99] Bovill, Carl (1996). Fractal Geometry in Architecture and Design. Boston, Birkäuser.

Table 20: Sierpinski Gasket, Additional Levels and Diamond Variation



Sierpinski Gasket, Level 2	Sierpinski Gasket, Level 3	Sierpinski Gasket, Free Form

The Sierpinski Gasket is different from other basic forms in its capability to create more uniquely shaped spaces that are not dependent on right angles but rather on a variation of acute and obtuse angles. This allows for greater variation in enclosure shapes and sizes and maximizes the potential number of layers of enclosures.

III. Flexible Armature

These forms seek to bring together the variety of arrangements that have already been presented, exploring the possibilities of having several of the proposals within the same system. The capability to realize more than one proposed form may lead to a system with greater flexibility and potential configurations that originally intended. Flexible armature refers to the elements that may remain fixed in the other designs, but in this design, would be rearrangeable as well. Thus, rather than focusing on specific configurations that have already been defined, this section outlines several design proposals focusing on how the flexible armature will move and how partitioning materials will be deployed. For each of these designs, the assumption is that each column can move to any point in the building-edge space much like the x-ray machine (Figure 51).

1. Armature moves horizontally, Material deploys horizontally

The first of these models focuses on a single column as the starting point for all walls to deploy from (Figure 8). The deployed material can be coplanar in two directions or in completely different directions to create configurations such as the Sierpinski Gasket and the Dragon Curve.

With the deployed material extending from a single column, the extending must be supported and deployed using some sort of a mechanism. The following figure provides a potential solution for deployment to confirm that this model warrants consideration and further exploration (Figure 9).

The rotation can be actuated from the post and material can be deployed using supports at the top of the material. This deploying material also eliminates the problem of walls with a fixed size, a problem with the swinging doors. The following figure reiterates this rotation and extension, but uses a second column to add further stability while also limiting the deployment of material to a single direction between the two (Figure 10).

Another consideration with the first design that uses a single column that is raised by the previous figure is the need to have a sufficiently robust deployment mechanism to support the material that is deployed.

Building on the last two examples with a material deployed between two columns and material deployed in multiple directions, this final method of horizontal deployment from movable posts uses a cluster of three columns (Figure 11).

The struggle with this final method of deployment is the size that a cluster of three columns is heavier and bulkier, potentially increasing the difficulty of the reconfiguration process.

2. Armature lifts out of space, Material may deploy from subsequent orientation

Another way for the armature to reconfigure is through vertical movements. Vertical movements allow the armature to completely lift out of the space to completely clear the floor to create a truly open and uninterrupted space. This complete clearing is a characteristic unique to this category of flexible armature. The following figure provides a summary of the three potential ways that armature can lift out of the space (Figure 12).

Each of these lifting methods creates a partitioning element through the deployment of material between two columns; material is deployed when the columns are pulled apart. In addition, these methods also include a horizontally deploying capability as shown in the "Double Column Extension Method."

The first method lifts the armature directly out of the space without changing orientation. The advantage of this method will become more apparent through subsequent discussion on the disadvantages of the remaining two methods. The drawback with this design is the space needed to store these columns once they have been withdrawn upwards; this space will need to be as tall as the space below to completely remove the columns thus creating an storage space above with little flexibility and usefulness.

For the second and third methods, the armature is extracted from the space by rotating the armature upwards. The exact direction of the rotation differentiates the second design from the third. In the second design, one column ends below the other allowing for vertical deployment of material much like a window shade (Figure 13).

In the third design, the pair of columns is rotated to the side and so that the columns end up side by side. When the columns are separated and the material is deployed, the material forms a horizontal plane to create a canopy or ceiling. This horizontal deployment creates a form not discussed in the performance specifications. Although not mentioned earlier, this design may allow this reprogrammable building edge to extend beyond the defined limits if the columns can extend out of the space to essentially create an awning. An awning provides a partially shaded or sheltered space for outdoor activities and sitting spaces.

Design Evaluation

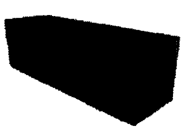
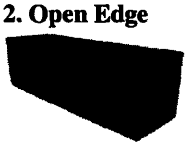
To evaluate each design proposal, the design concept is first assessed as a whole with some reference to the relative strengths and weakness of the other designs. Then, each design that still merits consideration is assessed against the relevant performance specifications. Through this process, the most promising architectural design will emerge for further exploration and detailing and a subsequent mechanical design process.

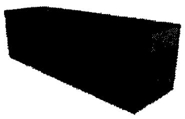
1. Circles

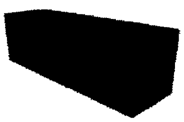
The design of the system based on circles creates many visually appealing models but obviously fails to best achieve the aims of this design project: a highly flexible space. The models propose exciting and unique reconfigurations of space, but the rounded edges created by these circular walls are not conducive for maximizing space with furniture or may require customized furniture, increasing the cost of this design. In addition, the spaces between circles or at intersections of circles often leave some space that is difficult to use, or in other words, leave dead space. Consequently, as this fractal system of circles lacks fails to fully use the building-edge space, this fractal system of circles is removed from consideration.

2. Dragon Curve

The dragon curve is unique for its layering of elements at varying depths into the building-edge space and the systematic size variation of edge conditions. The primary drawback of this model is the number of separate walls that may be needed to achieve the various shapes. Further exploration and modeling will aid the understanding of the true complexity of these designs and their configurability. As this complexity may contribute to the flexibility of the space, rather than providing grounds for elimination, this complexity warrants further consideration and evaluation against the performance specifications. The following table rates the dragon curve in its ability to achieve the defined specifications.

Performance Specification	**Measure of Success for Evaluation**	**Rating (1-5, 5 = yes)**
FORM (The Dragon Curve can generally achieve these forms simultaneously)		
1. Line/Sealed Edge 	Can this edge be completely sealed?	5
2. Open Edge 	Does this edge offer complete physical and visual access to interior?	2
3. Stalls	Does this edge provide sufficient separation for simultaneous independent activities?	5

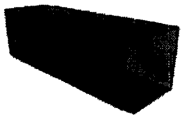
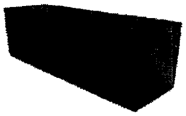
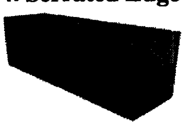
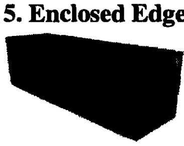
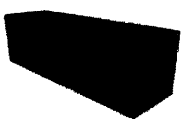


4. Serrated Edge		
	Does this edge provide sufficient enclaves for activities on both the interior and exterior?	5
5. Enclosed Edge/Modules		
	Does this edge create completely enclosed spaces where independent activities can occur without outside distractions?	5
6. Free Form Edges		
	How well can this edge create shapes that are not part of the initial set of pre-defined configurations?	2
	ENVIRONMENTAL STANDARDS	
Interior Standards		
2. Provision of Shade	Does the interior space provide refuge from direct sunlight?	5
	USAGE	
1. Programmability	How many distinct configurations are possible? (How many pre-determined arrangements?)	5
2. Flexibility	Can this system create configurations outside the pre-determined and pre-set configurations?	3
TOTAL		37

This systematic evaluation of the dragon curve warrants some explanation for the assigned ratings. In general, the ratings of 5 simply indicate that such designs are possible. The lower ratings for a open edge, free form edge and flexibility are related to fact that this design concept is entirely based on the dragon curve; any deviations from the dragon curve would place the configuration in another category. In spite of the lower ratings for these categories, when a dragon curve edge is mechanically designed, it is likely that each of the three categories will be completely achievable.

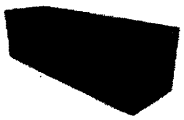
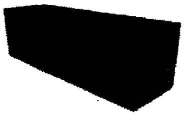
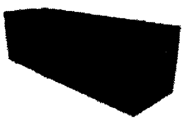
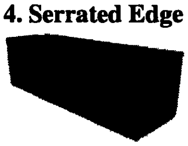
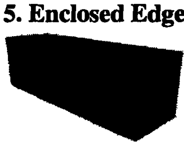
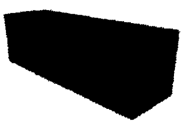
3. Sierpinski Gasket

The Sierpinski Gasket is a visually engaging design like the circles proposal and is also a design of varying depths and sizes like the dragon curve proposal. The largest draw back is the triangular shape that creates unusual angles that may require customized furniture, thus increasing costs. While the models do not demonstrate this, the Sierpinski Gasket is ideally of equilateral triangles, a characteristic that can be achieved when this system is constructed. Equilateral triangles will increase the versatility of any customized furniture and thus can somewhat minimize costs. A still more unique aspect of this model is the potential for varying shapes within the framework of the Sierpinski Gasket. The enclosure shapes include triangles and diamonds and portions of each for partitioning space. For this design proposal, while the unusual shape is a drawback, it is also a unique advantage, thus warranting this design for further assessment. The following table evaluates this model against the performance specifications.

Performance Specification	Measure of Success for Evaluation	Rating (1-5, 5 = yes)
	FORM (The Sierpinski Gasket can achieve these forms simultaneously)	
1. Line/Sealed Edge 	Can this edge be completely sealed?	5
2. Open Edge 	Does this edge offer complete physical and visual access to interior?	5
3. Stalls 	Does this edge provide sufficient separation for simultaneous independent activities?	5
4. Serrated Edge 	Does this edge provide sufficient enclaves for activities on both the interior and exterior?	5
5. Enclosed Edge/Modules 	Does this edge create completely enclosed spaces where independent activities can occur without outside distractions?	5
6. Free Form Edges 	How well can this edge create shapes that are not part of the initial set of pre-defined configurations?	5
	ENVIRONMENTAL STANDARDS	
Interior Standards		
2. Provision of Shade	Does the interior space provide refuge from direct sunlight?	5
	USAGE	
1. Programmability	How many distinct configurations are possible? (How many pre-determined arrangements?)	6+
2. Flexibility	Can this system create configurations outside the pre-determined and pre-set configurations?	5
TOTAL		46+

4. Flexible Armature

Inherent in its conceptual design, a system with flexible armature naturally increases the flexibility of a space over its stationary counterparts. This proposal is really a proposal to build a system that can achieve each of the previous models that are based on straight edge walls, or in other words, every model except the one based on circular walls. Any of the configurations possible with the relevant designs will also be possible with this system. This characteristic alone is sufficient to justify proceeding to the next stage of evaluation, the rating of this building-edge design against the performance specifications. The following table conducts this evaluation.

Performance Specification	Measure of Success for Evaluation	Rating (1-5, 5 = yes)
	FORM	
1. Line/Sealed Edge 	Can this edge be completely sealed?	5
2. Open Edge 	Does this edge offer complete physical and visual access to interior?	5
3. Stalls 	Does this edge provide sufficient separation for simultaneous independent activities?	5
4. Serrated Edge 	Does this edge provide sufficient enclaves for activities on both the interior and exterior?	5
5. Enclosed Edge/Modules 	Does this edge create completely enclosed spaces where independent activities can occur without outside distractions?	5
6. Free Form Edges 	How well can this edge create shapes that are not part of the initial set of pre-defined configurations?	5
	ENVIRONMENTAL STANDARDS	
Interior Standards		
2. Provision of Shade	Does the interior space provide refuge from direct sunlight?	5
	USAGE	
1. Programmability	How many distinct configurations are possible? (How many pre-determined arrangements?)	11+

2. Flexibility	Can this system create configurations outside the pre-determined and pre-set configurations?	5
TOTAL		51+

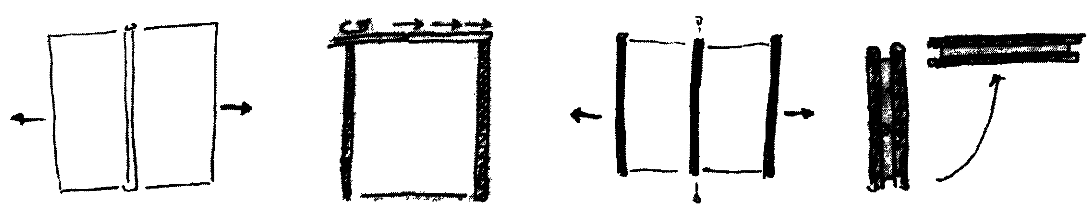
Most Promising Design

Through the evaluation process, this thesis has determined that the most promising design is the system of flexible armature comprised of columns and deployable material. A general framework of function must be defined in greater detail before proceeding to the mechanical design. This framework includes how the columns will function, how they will be clustered, and the number of columns.

II. Column Function

Column function is dependent on how the material is deployed, retracted and stored. There were four potential solutions. The first solution involves a single column with material extending outward by some mechanism in one or two directions. The second solution uses a pair of columns with material stretched between them; the material stored within the columns is deployed as the columns are pulled away from one another. Similar to the prior solution, the third solution employs a cluster of three columns with two segments of material stretched between the three, or in other words, a center column with material deployed as the other two columns are pulled away. The final solution is also based on the second solution, but with an added hinge at the top to lift the columns out of the space to both clear the space and to allow vertical or horizontal deployment. The following table summarizes these column systems.

Table 21: Four Potential Column Systems for Wall Deployment



Extending Walls	2-Column, Material Stretched Between	3-Column, 2-Direction Material Deployment	Hinged Columns

To select a column system for further design, the feasibility and drawbacks of each of these column and material deployment designs are evaluated. As noted before, the largest concern of the extending wall system is whether the mechanisms for extending the wall can be strong enough. The 2-column design is promising as long as material deployment is actuated by the separation of the columns rather than an extending mechanism as noted in the diagram; using the columns for deployment allows the system to be sturdier with two firmly fixed material holders. The 3-column design is similar to the 2-column design and is equally as promising; the only drawback is the increased number of columns that may increase the density of columns and size of column systems resulting in crowding of the building-edge space. Finally, the hinged column is based on the promising 2-column design, but the hinging action is difficult to achieve cleanly; the following diagram demonstrates the obstacles for a hinged system (Figure 14).

These diagrams illustrate the design process through which the hinged column was eliminated from consideration. The design evolved through consideration of the functional requirements of a hinged pair of columns. Horizontal deployment was determined feasible using an existing track system, but horizontal deployment where tracks already exist will for the most part deploy material below a ceiling, a pointless effort. Exploration of vertical deployment revealed the complexity of mechanical design necessary for realizing this concept. Consequently, this investigation confirmed that the hinged column would be unsuitable and that a 2-column material deployment system would best serve this building-edge system.

II. Column/Cluster Count

The number of columns or clusters necessary is dependent on the base configurations that ought to be creatable by this system. An infinite number of columns would allow infinite configurations, but presumably, there is a threshold at which additional columns will no longer contribute to the flexibility of the system. This section seeks to deduce that threshold for this system so that flexibility is optimized without excess clutter, cost and complexity. Through systematic diagramming of potential configurations, important nodes are identified and a sufficient number of columns is established.

Surveying the higher level dragon curves and Sierpinski Gaskets distinct walls surfaces are identified. The basic architectural forms as defined by the performance specifications are much less complicated and will thus require fewer segments. Consequently, their column number requirements are not investigated. The following diagrams document the exploration of the highest levels of the dragon curve (Figure 55) and Sierpinski Gasket (Figure 56).

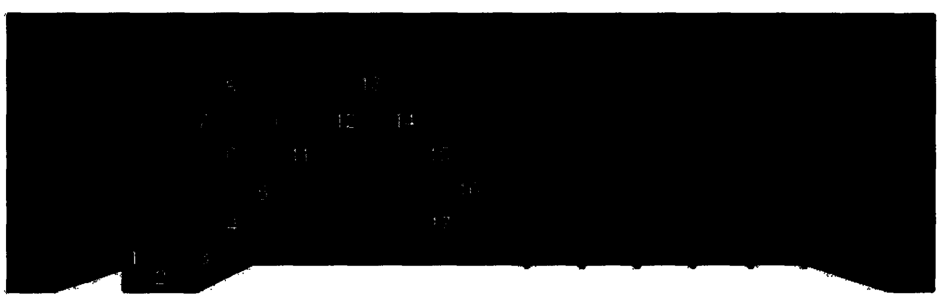


Figure 55. Dragon Curve with 17 Distinct Wall Segments Numbered

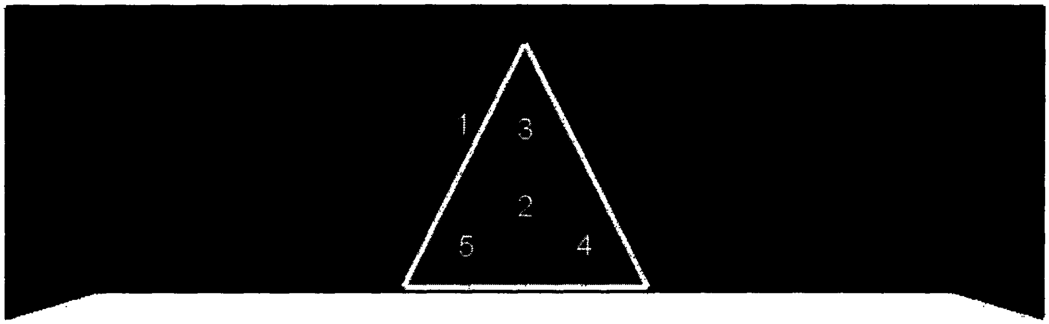


Figure 56. Sierpinski Gasket with 5 Triangles (3 segments each) Labeled

Looking at the number of distinct line segments which will form wall segments in this building-edge, the number of necessary column pairs can be calculated. For the dragon curve, the fourth level requires 16 or 17 line segments; segments 6 and 11 or 5 and 9 can be merged to be a single, longer segment. The number of segments in the third level of the Sierpinski Gasket is determined through counting the number of distinct triangles, where each side of the triangle is a wall segment or a pair of columns. Each set of 5 triangles requires 15 line segments. Since there are three sets, there are a total of 45 line segments necessary to create this model. Thus, the Sierpinski Gasket is the limiting factor, requiring many additional columns beyond that of the other models.

The high number of segments needed to construct the Sierpinski Gasket presents two problems: high column density that may clutter the space and many columns will increase building and maintenance costs. Checking the size of the triangles in this system, the smaller triangles are found to be around 8 feet along their longest side; these triangular enclosures may not provide especially useful spaces because of their small size. Thus, it is sufficient to construct two triangles which may potentially be widened in this space.

With this concession, the dragon curve becomes the limiting factor with a minimum of 16 segments for a single curve and 32 segments for two. Thirty-two segments, or 64 columns, is a more reasonable number. Consequently, this system will be designed with 32 rearrangeable column pairs.