The Chandelier:
Toward a Digitally Conceived Physical Performance Object

Steven L. Pliam

Bachelor of Arts, University of Minnesota, 1989
Master of Architecture, Virginia Polytechnic Institute, 2000

Submitted to the program in Media Arts and Sciences,
School of Architecture and Planning,
in partial fulfillment of the requirements for the degree of
Master of Science in Media Arts and Sciences at the
Massachusetts Institute of Technology
August 2007

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Abstract

In the performing arts, the relationship that is established between what is seen and what is heard must be experienced to fully appreciate and understand the aesthetics of performance. Actual physical objects such as musical instruments, lights, elements of the set, props, and people provide the visual associations and a tangible reality which can enhance the musical elements in a performance. This thesis proposes that new and artistic physical objects can, in themselves, be designed to perform. It introduces the Chandelier, a kinetic sculpture, a central set piece for a new opera, a new kind of musical instrument, and an object that performs. The piece moves and changes shape through mechanical action and the designed interplay between surfaces and light. It is intended to be interacted with by musicians and players of the opera. This thesis also explores the design process and evolution of the Chandelier with a primary objective of realizing a constructible, physical performance object through an authentic and abstruse digital conception. It is a conception not of a static nature, but incorporates a dynamic sense of changeable form through coordinated elements of light, mechanics, and sculpture.

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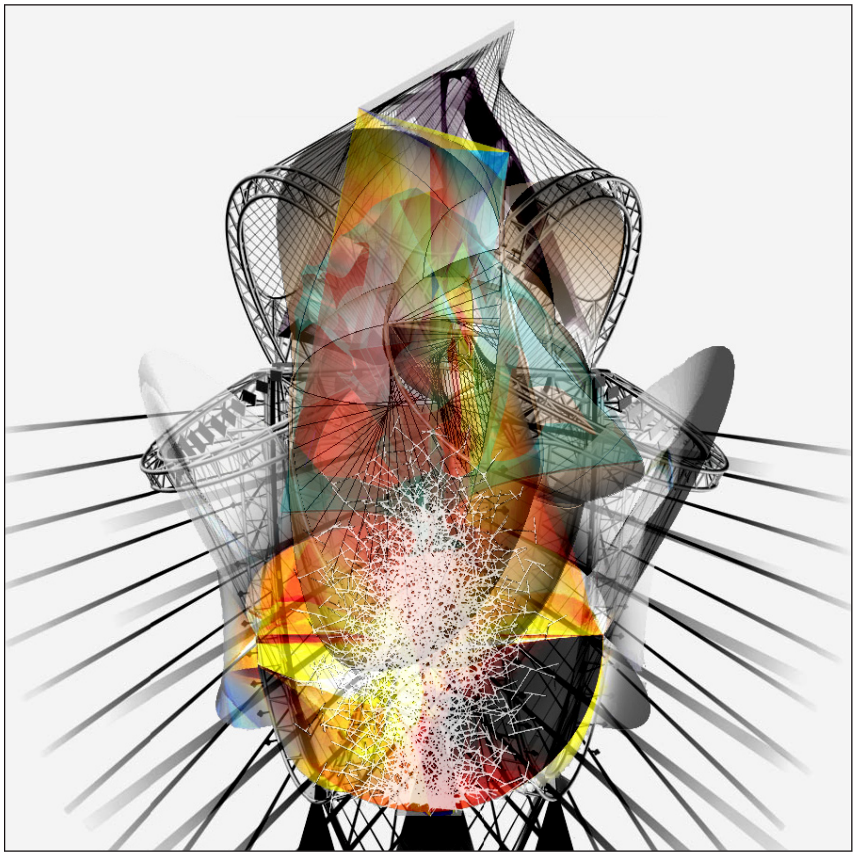
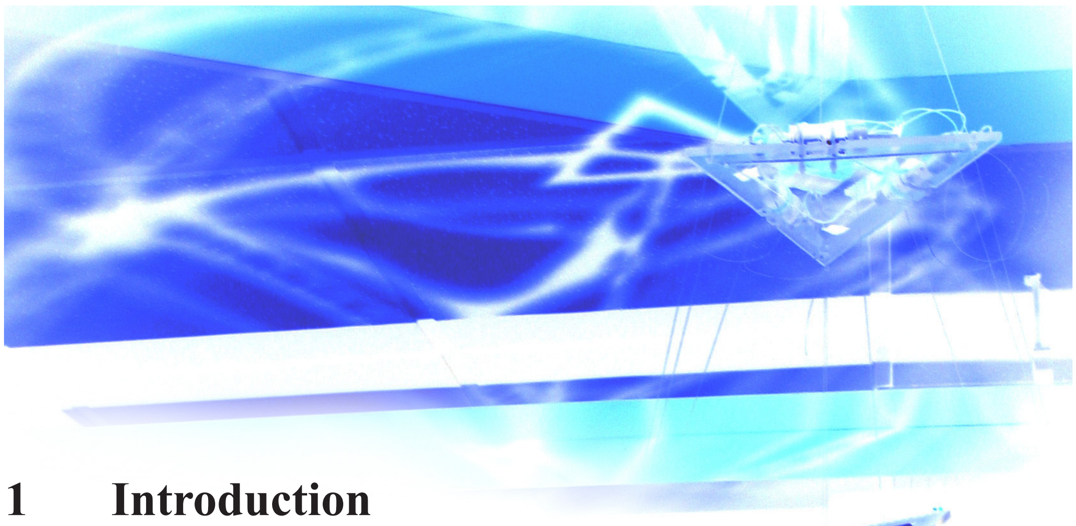
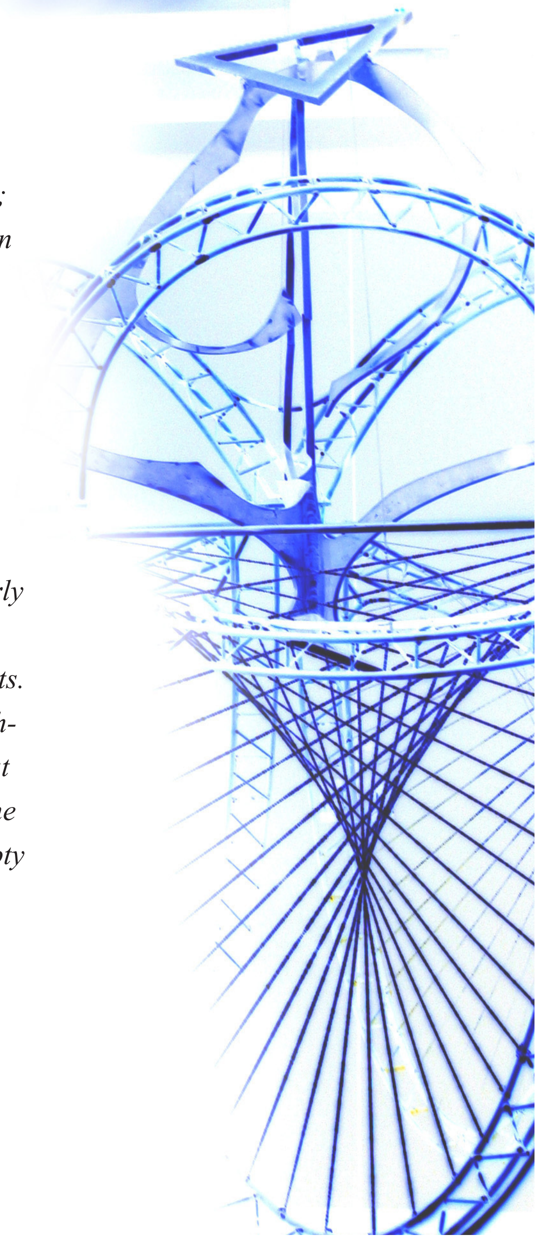




Chapter 1 Introduction



The scientist does not study Nature because it is useful; he studies it because he delights in it, and he delights in it because it is beautiful. If Nature were not beautiful, it would not be worth knowing, and if Nature were not worth knowing, life would not be worth living.

--Henri Poincaré, 1901

It is certain that mathematics generally, and particularly geometry, owes its existence to the need which was felt of learning something about the behavior of real objects. The very word geometry, which, of course, means earth-measuring, proves this. ...geometry [mathematics] must be stripped of its merely logical-formal character by the coordination of real objects of experience with the empty conceptual schemata of axiomatic geometry.

--Albert Einstein, 1921

1.1 Motivation

The idea of designing a piece of art, and particularly sculpture, as an authentic conception of the digital domain, that is, a conception that is exclusively derived from computation, has interested me for a long time. I have had first-hand experience working for a world-class, visionary architect who has made a lot of use of digital modeling tools to enable the design and construction of his projects. Frank Gehry is known for his geometrically challenging, highly sculptural architecture [Dal Co 2003]. However, he has never really exploited the special capabilities of digital modeling as a design medium. His conceptions have always occurred through the modeling and manipulation of physical materials. In this thesis, my aim is different. The primary interest that drives the evolution of the work in this thesis is the attempt to create a compelling physical performance object which is entirely constructible, but an object which is derived from the exploitation of the digital modeling medium. Of particular interest is to give material reality to a highly dematerialized, abstruse three dimensional digital form.

The medium of three dimensional digital modeling, like so many other digital tools, extends our abilities to conceive and create uniquely compelling ideas for the arts. The medium has a particularly powerful ability to manipulate and produce geometries which are highly complex. I have always had a great interest in geometry and its relationship to architecture and the arts, and have a strong predilection for geometric form in sculpture. A great many sculptors share the same inclination. It is therefore quite easy to see why I have moved toward the digital modeling medium as a means to artistic design.

> If the object of the modern practical musicians is, as they say, to delight the sense of hearing with the variety of consonances, and if this property of tickling (for it cannot with truth be called delight in any other sense) resides in a simple piece of hollow wood over which are stretched four, six, or more strings of the gut of a dumb beast or of some other material, disposed according to the nature of the harmonic

> numbers, or in a given number of natural reeds or of artificial ones made of wood, metal, or some other material, divided by proportioned and suitable measures, with a little air blowing inside of them while they are touched or struck by the clumsy and untutored hand of some base idiot or other, then let this object of delighting with the variety of their harmonies be abandoned to these instruments, for being without sense, movement, intellect, speech, discourse, reason, or soul, they are capable of nothing else. But let men, who have been endowed by nature with all these excellent and noble parts, endeavor to use them not merely to delight, but as imitators of the good ancients, to improve at the same time, for they have the capacity to do this and in doing otherwise they are acting contrary to nature, which is the handmaiden of God.
>
> -- Vincenzo Galilei, Dialogo della musica antica e della moderna, 1581

According to Jamie James [James 1993], these two very long sentences of sarcasm, by Galilei, led directly to the birth of opera. These words, apparently, incited the noble personages of Florence, at the time, to study and patronize the musical arts as well as to hold them worthy of great esteem. Galilei was a member of the Camerata, a salon of one of the nobles, which began commissioning the first operas. What cannot be missed in these words is the almost obsessive focus on objects, namely the physical objects of instruments. Though somewhat nebulous, Galilei seems to regard the use of these objects, in terms of movement, intellect, and reason, as essential to the success of performance.

The performing arts have an intrinsic association with the physical environment. Even the concert hall or the dance theater can be thought to constitute the architectural physicality of an artistic performance. Architecture and performance objects, such as stage props or musical instruments, are important physical elements for the execution of an opera, dance performance, or concert music. They are an integral part of the experience. It is clear that a music or video recording of a concert or dance lacks the physical connection to the actual performance. Only in the presence of these elemental physical actions is it possible for an audience to fully realize the performance experience [Mazzola, Göller 2002]. If this assumption is valid, the possibilities for new and interesting objects of art that could perform expressive actions which would relate directly to musical or other performance events arise. Such objects might extend the physical connection that the audience would have with performance art in profound and unprecedented ways.

1.2 The Chandelier

This thesis introduces the Chandelier, a performance object, a kinetic sculpture, a central set piece for a new opera, and a new kind of musical instrument. It moves and changes shape through mechanical action and designed illumination. It is intended to be interacted with by musicians and players of the opera.

This newly invented performance object became the means through which I could explore the ideas and objectives that motivated the work of this thesis. As an object of sculpture, it embodies several important themes of the opera. As a new kind of musical instrument, it explores new sonic timbres as well as new kinds of mechanisms to produce those timbres. Much of the thinking that went into the design has been concerned with the impact that the chandelier, as a prominent physical presence, would have as a performing object. It is designed to move and change shape to convey a sense of metamorphosis which will coordinate with narrative and musical ideas consisted in the opera. Another significant aspect of this set piece is that it physically produces musical sounds through electromagnetic excitation and other actuated stimulation of piano-like strings. The result of this design, it is hoped, will contribute significantly to the overall operatic experience through giving physical form to the narrative and musical events within it.

1.3 Organization of This Thesis

This thesis is divided into five chapters:

Chapter 1: Introduction

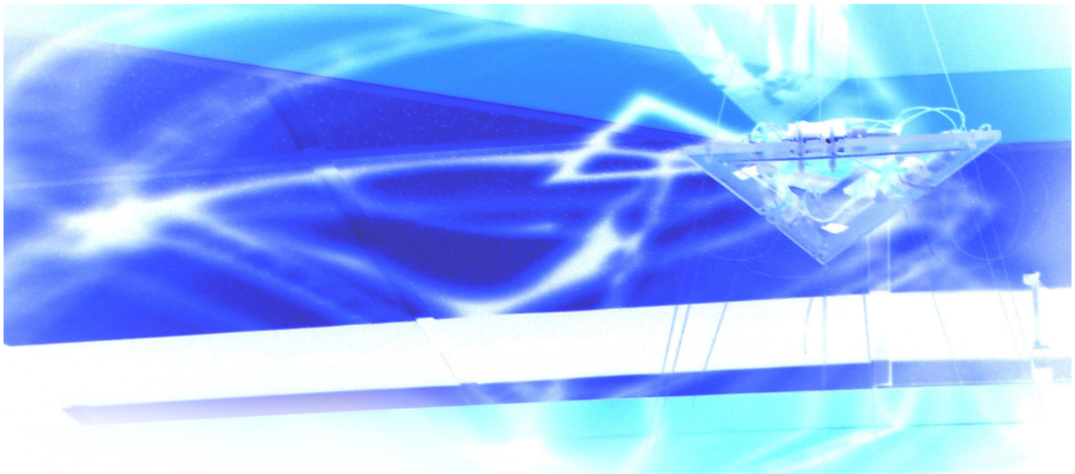
Chapter 2: Background and Related Work
Describes work, primarily from others, that serves as relevant background. This work is both technical and aesthetic, even artistic, and has significantly informed the work of this thesis as well as influenced the development of the Chandelier.

Chapter 3: Parameters of Design
Describes both the formal and mechanical principles which have guided the process of designing the Chandelier. Describes the aesthetic and collaborative parameters which were a significant part of the design experience.

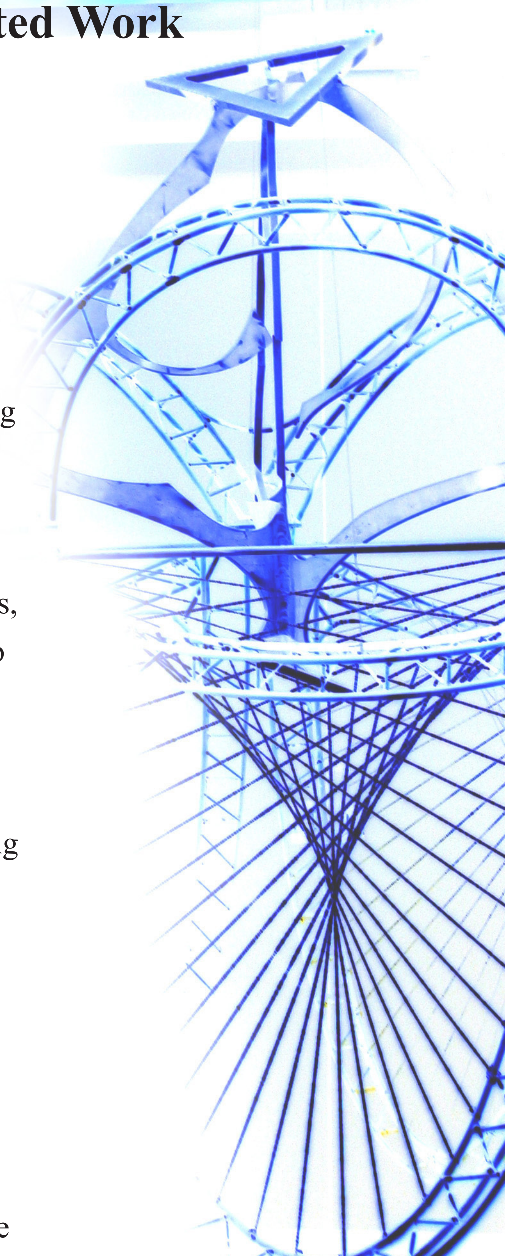
Chapter 4: Process of Execution
Provides a detailed account of the evolution, constraints, discoveries, and resolutions of the design process and construction of the Chandelier. Discusses relevant technologies that factored into the process.

Chapter 5: Conclusion
Offers an evaluation argument and concluding thoughts about the aesthetics, technology, and future of the Chandelier project.

Companion URL: <http://web.media.mit.edu/~pliam/res/clier.html>
Provides links to several animations which present many of the images and ideas in this thesis.



Chapter 2 Background and Related Work



2.1 Challenging Form Through Digital Modeling

There have been many investigations into the possibilities for creating sculptural form, including free-form architecture, using three dimensional (3D) digital modeling computation as well as standard Computer Aided Design (CAD) software. The algorithms or functions that are available in most professional level 3D CAD modelers offer a very extensive library of modeling tools, operations, and mathematical transformations which can be utilized to generate very interesting and complex three dimensional artistic forms.

Much of the existing work that has been done in attempting to achieve authentically digital, original, and compelling 3D forms is related heavily to the metaphor of physical sculpting. Much of the research is centered around interactive and intuitive modeling using specialized human and computer interfaces. Galyean et al. developed a modeling system which enables a user to sculpt a solid material represented by voxel data by using virtual digital sculpting tools. A user can design 3D objects with intuitive methods similar to real sculpting, because a 3D input device controls the sculpting tools [Galyean, Hughes 1991]. However, the problem with voxel-based data is that surfaces and curves are not smooth and the concept becomes the same as a pixel map. Wang et al. developed a volume sculpting tool as well. This was based on a concept of sculpting a solid material which was also voxel-based. As an interface, the method of manipulation feels quite limiting if you compare it to real physical sculpting. That is because the user is still forced to manipulate 3D objects with the antiquated, somewhat sterile input/output devices of the mouse and LCD display [Wang, Kaufman 1995]. Bill and Lodha et al. used polygonal models to develop a sculpting metaphor. With this way of working, the user is actually able to alter the topology of the surface; however, they are still working with a tessellated approximation of a smooth surface and are forced to deal with cumbersome connectivity issues [Bill, Lodha 1995]. Noble developed another modeling system which enables the user to deform parametric surfaces with a much more direct, on-surface manipulation. The difficulty here is when the user tries to anticipate and predict the results of their manipulation; but the system does lead to a very convincing clay modeling metaphor. Perhaps, its greatest limitation is that the user cannot modify the topology of the deformed object with this kind of space deformation technique [Nobel, Clapworthy 1998]. One of the more successful 3D modeling techniques has been developed by Matsumiya, Takemura, and Yokoya. They have created a new free-form interactive modeling technique based on the metaphor of clay work. This immersive modeling system enables the user to interactively and intuitively design 3D solid objects with curved surfaces by using a finger. Also, their system defines shape deformation and smooth free-form surfaces with simple mathematical data [Matsumiya, Takemura, Yokoya 2000]. As I will discuss later in Section 4.6, minimizing the quantity and complexity of the mathematical data becomes extremely important for the specification of a constructible object. Chen and Sun have developed a virtual haptic sculpting system which emulates sculpting material interactions and behavior to include real-time melting, burning, stamping, painting, and peeling. The system uses an off-the-shelf desktop, haptic human interface. [Chen, Sun 2002]. Others have moved closer to relying on interactive graphic displays to give feedback to the user to help him/her sculpt more intuitively artistic forms. The work of Rappoport and Spitz [Rappoport, Spitz 1997] gives much emphasis to the rapid interactive visualization of the model for the user in real-time. Schkolne, Pruett, and Schröder have directly targeted the needs and interests of artists with their “Surface Drawing” system which allows the user to create very unusual, interesting 3D organic shapes with tangible hand tools. [Schkolne, Pruett, Schröder 2001].

Figure 2.1 Chen, Sculpting system using the PHANToM Desktop haptic interface.

The research previously discussed, while certainly effective for creating original modeled forms, depends mostly on a direct interface activity which, for the most part, tries to emulate the sculpting metaphor. Therein may lie its greatest limitation with regard to the objective of the research in this thesis. The fundamental interest here is to identify and utilize digital modeling techniques which have the ability to create normally inconceivable, abstruse forms that can nevertheless be constructed. Inevitably, the construction or prototyping of the object will help inform us about the nature of the form. Given the breadth of available 3D modeling tools which implement mathematical algorithms to allow the user to create geometrically complex and beautiful forms, it is believed by many artists that this medium provides a means to a new realm of visual art. Several people have developed techniques and software to model with mathematically based algorithms. Terzopoulos and Qin have developed an interactive sculpting system using a “dynamic” NURBS (Non Uniform Rational B-Spline) model which allows the user to sculpt shapes with NURBS mathematics. [Terzopoulos, Qin 1994]. Adams and

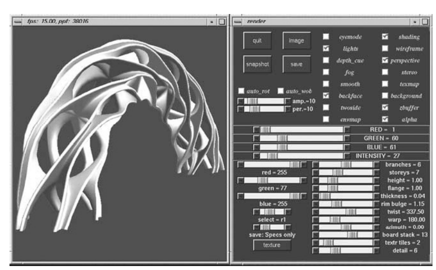


Figure 2.2 Carlo Séquin, Sculpture Generator I software user interface.

Dutré have applied interactive Boolean operations on surface bounded solids which allows for highly complex shapes to be sculpted with very robust mathematical data. [Adams, Dutré 2003].

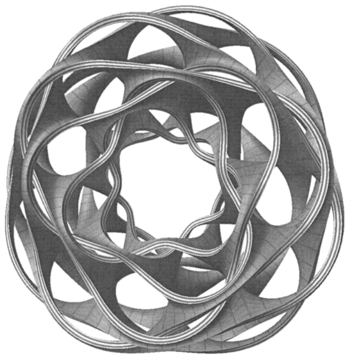


Figure 2.3 Carlo Séquin, *Heptoroid.*

There have been a number of fine art sculptors who have actively pursued the challenge of realizing abstruse, sculptural form that would normally be impossible, or exceedingly difficult, without the use of 3D CAD tools. Carlo H. Séquin, an artist and professor of Arts and Sciences at the University of California, Berkeley, has made a very significant contribution to both the 3D modeling technology as well as the body of this kind of sculptural art [Séquin 2001]. As a scientist, he became very interested in the beauty and complexity of various mathematical models and geometries. Eventually, his increasing interest in computer graphics compelled him to exploit the power of 3D CAD to help him generate physical

Figure 2.4 Carlo Séquin, *Borromean Torus.*

Figure 2.5 Carlo Séquin, Snow sculpture: *Whirled White Web.*

Figure 2.7 Carlo Séquin, Untitled 3D CAD rendering.

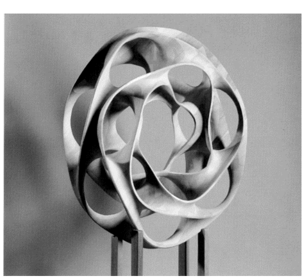


Figure 2.6 Brent Collins, Heptoroid 1998.

sculpture that would express the beauty of these complex mathematical models [Séquin 2000]. Brent Collins, who is a sculptor and an academic, has written about how Séquin's techniques and 3D CAD have greatly furthered the evolution of his art beyond what would have previously been possible. He discusses the development of his sculpture over a period of several decades, as an intuitive art of visual mathematics. He also discusses his collaboration with Séquin which has led to a virtual prototyping system that has allowed the material realization of his works [Collins 1997]. Séquin most recently has taken the creation of abstruse sculpture to a new level in fully integrating 3D CAD processes with rapid prototyping so that sculptors and other visual artists will have a means to a truly three dimensional, physical manifestation of their work [Séquin 2005]. Other sculptors have followed lines similar to Séquin in producing conceptually difficult works through the medium of 3D CAD. Helaman Ferguson has produced challenging, mathematically inspired, and free-form works in bronze and stone. Not only are his sculptures conceived digitally to obtain a formally difficult geometric conception, but the physical manifestations of his work constitute a true mastery of the entire craft of digital prototyping on through to fabrication [Ferguson 1994]. A Swedish ceramic artist, Eva Hild, has created large scale ceramic sculptures based on conceptually challenging ideas derived with 3D CAD [Hild 2007]. George Hart conceives his sculptural works from the 3D CAD medium as well. He claims that the medium has helped him to realize a "geometric aesthetic" which would otherwise be impossible through conventional media. In a talk given to the Symposium on Computational Geometry in 2001, he proclaimed [Hart 2001]:

> I am a full-time sculptor creating works that manifest what I call the geometric aesthetic. This aesthetic celebrates the beauty of geometry and spatial rationality. I seek to produce novel forms which engage the viewer visually and have an underlying coherence based on symmetric three-dimensional mathematical structures. Internal relationships between the components of a sculpture can provide a depth to the work, leading the viewer

Figure 2.8 Eva Hild, *Stoneware* 2003.

Figure 2.9 Carlo Séquin, *Totem 3 Bronze* 2004.

Figure 2.10 Eva Hild, Sculpture: title unknown.

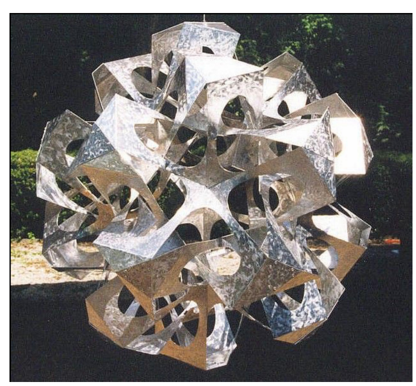


Figure 2.11 George Hart, *Whoville*, aluminum, The form derives from an icosahedron and dodecahedron in a mutually dual position.

to return again and again, each time seeing deeper into the piece. In addition, the viewer is led to ask questions of a mathematical nature about the patterns he or she finds.

Friedman [Friedman 1998] discusses the unique quality that certain kinds of conceptually abstruse sculptural art will have which allows the viewer to see in new ways. "Hypersculpture," as he refers to it, is a type that represents a given object from several points of view at once. It is, in this sense, four dimensional sculpture. The 3D CAD medium facilitates the modeling of this extremely complex geometry which can then be concretized in physical form. Friedman highlights the fact that seeing is of basic importance in mathematics just as in art, and certain mathematical forms can be seen as ideas for generating art forms. He introduces the idea of "hyperseeing," which is a more complete all-around way of seeing from multiple viewpoints; and it is conditioned by viewing hypersculpture. David and Harriet Brisson also contributed sculptural works and criticism that were at the forefront of visualizing higher dimensional art forms. They advocated the notion that through the creation of physical objects and the tangible knowledge that we acquire from them, it is possible to visualize and comprehend very complex geometric ideas. Such ideas could be initially explored within the 3D CAD medium [Brisson 1992].

I have conducted a study of several hyper-sculptural objects which required 3D CAD techniques to visualize and construct. One of the more complex constructions was a four dimensional analog to the fifth platonic solid body, the dodecahedron. It is a highly mathematically based entity that contains 120 three dimensional dodecahedron cells which are seamlessly bound together, and completely fill the internal volume which is defined by the limits of an outer dodecahedron. This polytope (n-dimensional analog to a polyhedron) can be understood as

Figure 2.12 Arthur Silverman, *Attitudes* 1996.

Figure 2.13 Charles Ginnever, *Rashomon* 1998.

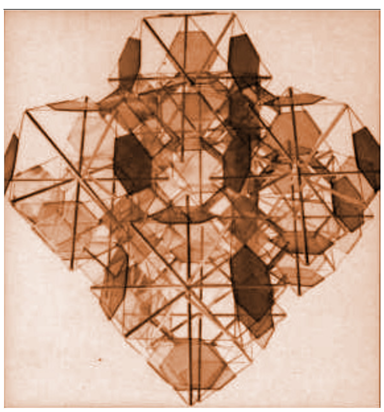


Figure 2.14 Harriet Brisson, *Great Rhombicuboctahedra and Octagonal Prisms*, This space-filling structure divides space perfectly in half. It is impossible to differentiate the form from the space between, since the two are identical.

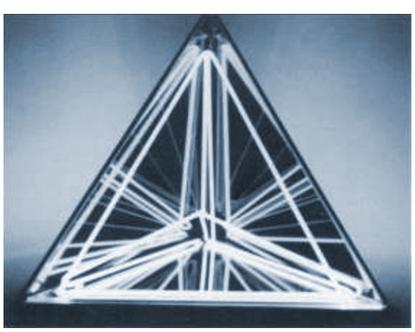
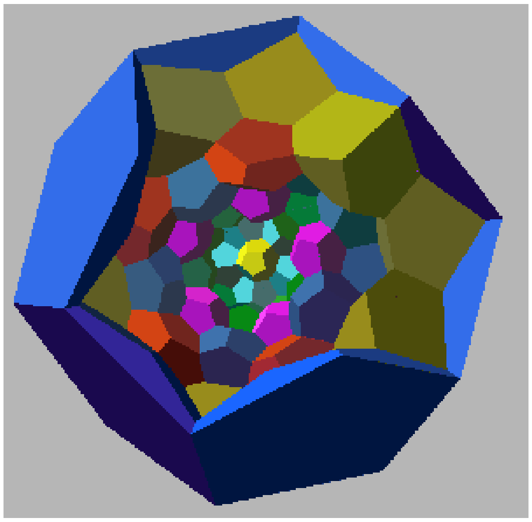


Figure 2.15 Harriet Brisson, *Pentahedroid*, four-dimensional tetrahedron.



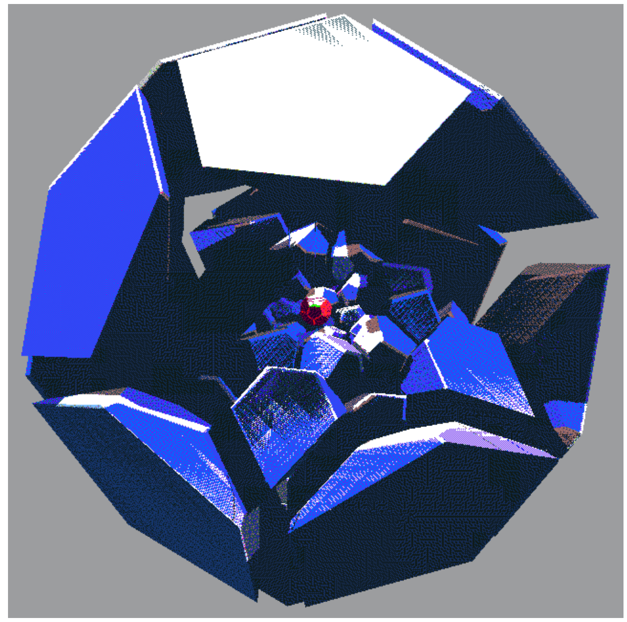


Figure 2.16 3D CAD deconstructions of a hyper-dodecahedron.

a projection of a four dimensional dodecahedron onto three dimensional space [Pliam 1995].

2.2 Visual Objects in Connection with Musical Performance

Live performance, of any kind, has an intrinsic association with physical events. These events rely on the action of objects, whether they are musical instruments, people, or stage props in an opera. The action of these objects constitutes a translation of the abstract, formal phenomenon of music and choreographic concepts into a tangible, physical manifestation. The audience can make sense of this manifestation through the intellect, and the resulting experience is the aesthetic apprehension of performance. Just as music must be composed, it is often suggested that performance must be designed. Johnston suggests that musical performance constitutes a “design problem” that must be dealt with through the visualization and physicalization of musical events in order to give meaning to a performance [Johnston, Amitani, Edmonds 2007]. What emerges from this notion is the possibility for innovative and meaningful artistic objects that could perform expressive actions that would relate directly to a choreography or auditory events. Such objects would extend the physical connection that the audience would have with the performance. Mazzola and Göller make a convincing argument for the necessity of physical performance elements, including musicians, singers, and dancers, in giving meaningful interpretation to the abstract symbols of a musical score. They make the claim that an artistic or musical performance is the physical execution of a work of art; and therefore, any visually compelling object which serves to connect the audience with the abstractions of music can be a viable enhancement as well as an integral component of the performance [Mazzola, Göller 2002]. Dance choreography, in concept, tries to embody musical, as well as extra-musical, ideas through the coordinated movement of human beings; and it can be argued that the basis of this art form is to extend the physical connection with the music. Bahn [Bahn, Hahn, Trueman 2001] and Friberg [Friberg, Sundberg, Fryden 2000] make strong cases for the physical connection of music with the motion of the body, which becomes a vital and compelling physical constituent of the musical performance. Artistically constructed physical objects may be programmed to behave according to a choreography that provides a similar kind of physical connection to the music or other source material.

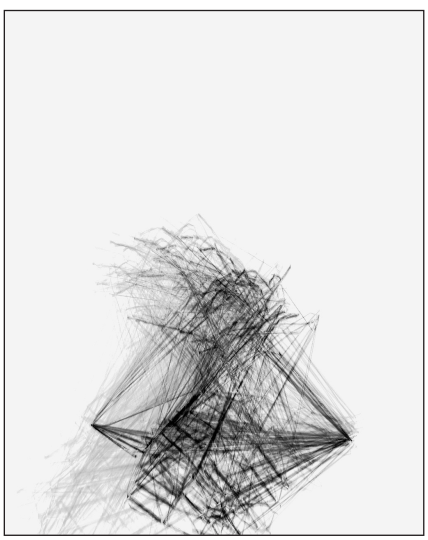


Figure 2.17 Marc Downie, from *Loops* art installation.

Real-time visual art which correlates to other sources in a performance, like music, is nothing new; and much excellent research has been done in this area. Marc Downie has taken the notion of choreography and applied it to real-time graphics that follow and respond to a musical score. There is no doubt that these compelling graphics give a strong visual, even cinematic, component to the musical performance [Downie 2005]. The effort to bring musical activity into the physical realm can be found in related research. Charles Bestor's work with installation art attempts to marry the tangible, spatial qualities of sculpture with the temporal qualities of a corresponding musical work. His pieces are, in essence, sculptural interpretations of the sonic material which is experienced and activated by the observer as he or she passes through the piece [Bestor 2003]. Poupyrev et al. developed an interactive sculptural piece which can be made to control musical events as well as express them. It takes the form of a horizontal bed that contains a set of transparent plastic rods which illuminate and move vertically according to how the user interacts with it. Yet it is also capable of changing shape and color according to various input material including music, thus behaving like a responsive kinetic sculpture. [Poupyrev, Nashida, Maruyama, Rekimoto, Yamaji 2004]. Similarly, Roosegaarde constructed a large wall sculpture which is made up of a massive two dimensional array of projecting rod elements that respond to a musical input which can either be raw audio or a MIDI score. The piece conveys a powerful, dynamic physical expression of the music. [Roosegaarde 2005].

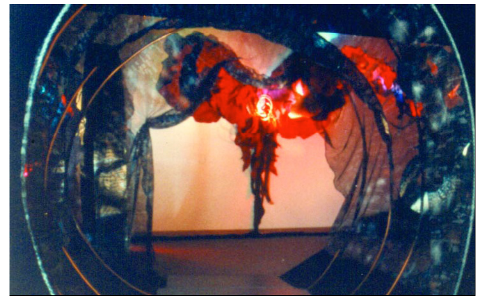


Figure 2.18 Charles Bestor, *Into the Labyrinth*, interactive art installation.

The relationship between musical instruments and their performance aesthetics has always been an important one. This is probably true primarily because there exists an inextricable connection between what is being heard, the physical actions of the performer, and how an instrument works to produce musical sound. Fletcher and Rossing provide much insight about how the physics of musical instruments are actually revealed in their design and construction. The physical construction then becomes a part of the aesthetic appreciation of how the sound is produced [Fletcher, Rossing 1998]. In the case of more traditional instruments, the visual observation of how a musician physically interacts with the mechanics of the instrument is a significant part of the overall aesthetic experience of a performance and gives a full appreciation of the tangible beauty of the instrument. Roger Scruton, [Scruton 1999] in his chapter on musical performance in his book *The Aesthetics of Music,* underscores the importance of the physical tangibility of various acoustic instruments with respect to how they enhance the experience of performance. However, with the development of electronic digital instruments, there has been something of a breakdown in this tangible relationship between the physicality of the act of playing an instrument and the sound that is created. As an example, the familiar piano-type keyboard has been reduced simply to an interface to access electronically generated sounds. In other words, it produces no sound of its own, physically, that the audience can connect to the action of the instrument. Since the actual creation of the sound happens within internal electronics, there is then very little to impart a visual description of how that sound is produced, and hence the quality of the tangible relationship is, in many cases, almost totally lost.

The experience of listening to music without any visual component to convey a physical reality can, of course, be very meaningful and satisfying. Recorded music, for example, certainly does have its benefits. In this form, as well as music that is created electronically, the listener deals with a highly distilled, pure, temporal composition of sonic events and textures. The nature of the musical perception might, in this particular sense, be more direct. As the late pianist and critic, Glenn Gould, points out, one of the greater benefits of recorded music may be in the insights which it gives to those perceptions as they relate more broadly to the past and future.

> Recordings deal with concepts through which the past is re-evaluated, and they concern notions about the future which will ultimately question even the validity of evaluation. [Gould 1966]

However, the qualities that may be most unique to these mediated, electronic forms of music relate to the altered roles of the participants involved, including the audience or listener. In the mid-1960s, Gould states an extremely prophetic summary about the significance of recorded music:

> Electronic Transmission [Recording] has already inspired a new concept of multiple-authorship responsibility in which the specific functions of the composer, the performer, and indeed the consumer overlap. We need only think for a moment of the manner in which the formerly separate roles of composer and performer are now automatically combined in electronic tape construction or, to give an example more topical than potential, the way in which the home listener is now able to exercise limited technical and, for that matter, critical judgments, courtesy of the modestly resourceful controls of his hi-fi. It will not, it seems to me, be very much longer before a more self-assertive streak is detected in the listener's participation, before, to give but one example, "do-it-yourself" tape editing is the prerogative of every reasonably conscientious consumer of recorded music (the Hausmusik activity of the future, perhaps!). And I would be most surprised if the consumer involvement were to terminate at that level. In fact, implicit in electronic culture is an acceptance of the idea of multilevel participation in the creative process. [Gould 1964]

There is an interesting implication in Gould's text. The inclination for the listener to assert judgment and exercise the ability to participate in the editing of recorded material may indicate a broader yearning to understand and obtain a deeper apprehension of the music. There is good reason to conclude that this yearning may be an inextricable condition of the experience of music. If the sensory ability of the eyes can be utilized to help satisfy this yearning, then perhaps the modalities of dance, opera, and film have something more to offer us in that experience.

With electronically created and recorded music, the listener only has the aural information from the ears. He or she does not have any visual indication about how the sounds are being created. There is not any visual affirmation to resonate with the qualitative aspects of the music, such as tempo change, articulation, and dynamics. These qualitative elements of musical expression can be appreciated during a performance, because they have an affinity with music cognition. Hiraga makes the claim that these are among the primary elements of music that influence human emotion, and hence, the experience of the listener [Hiraga, Matsuda 2004]. Bresin calls these same basic elements "expressive cues" which trigger the emotional response of the listeners; and such cues can be affirmed visually through the act of performance by musicians or dancers [Bresin, Friberg 2000]. Hiraga goes on to assert that the audience will actually be assisted in the aesthetic understanding of a performance by a visualization which coordinates with these qualitative musical elements of expression. Any visual cue which aligns with or echoes these expressive elements will enhance the emotional response of the audience. He goes further to say that such visual elements in a performance will actually aid the listener's experience and comprehension of the music [Hiraga, Matsuda 2004]. This enhanced experience through visual alignments with the qualitative aspects of tempo, articulation, and dynamics is not possible through the pure listening experience of a recording or digitally produced, sequenced music. Therefore, it may be reasonable to conclude that live performance and the multimedia forms of film and opera can offer a more integrated experience of the senses that will lead to greater comprehension. The coordination of different sensory elements in these genres would appear to equate to a greater whole than the sum of its constituents.

One basic problem that the design of the Chandelier has tried to address is the question of how to restore the aesthetic expression that only the action of physical objects can manifest in the performance of digital music, and thereby, help reestablish a meaningful connection between a physical aesthetic and the musical performance that would correspond with it. With respect to digital audio, sound is generated inside the electronics, so a corresponding choreography of objects could express those events visually. A new technologically based opera is the perfect context within which to explore such a choreography. It is not necessarily a goal for the Chandelier, or the entire set for that matter, to restore the sense or presence of a traditional musical instrument. That would essentially be trying to merely emulate a traditional experience. Rather, the aim here is to conceptualize a choreography of physical objects that would be 'interactive' in the sense that they would respond in real-time to musical/auditory material or other programmatic input in order to establish a tangible connection to it. Even though there would not be a literal recreation of a traditional musical instrument in performance, this could nevertheless serve to expand our notion of what a musical instrument might be through giving a compelling and meaningful physical reality to the material.

There has been much interest and research devoted to giving visual form to music. Much of this work has involved a graphic approach to the interpretation of musical form. As previously discussed, some of the research has attempted to correlate a more three dimensional, sculptural manifestation with such form. The research in this thesis is concerned not so much with graphic interpretations, but rather the action and movement of three dimensional objects, with the goal to develop a new physical means to express and coordinate with related events that are occurring in music, dance, or other action components of a performance piece. The objects then become an integral aspect of that performance.

2.3 Sculptural and Robotic Musical Instruments

Figure 2.19 Eric Singer, LEMUR musical robots.

Among other set pieces in the *Death and the Powers* opera, the Chandelier has, as one of its most important functions, the role of a musical instrument. It contains robotic components which operate to help produce the unique sounds that it makes. As it is also a piece of sculpture, the design has required a tenacious commitment to achieving a balance between the robotic requirements and the artistic intentions of the piece.

There have been numerous contributions to the field of musical robotics. Eric Singer has made a recent, but significant, contribution with the League of Electronic Musical Urban Robots (LEMUR). Similar to the robotic design elements of the Chandelier, Singer has implemented motors and solenoids to vibrate shakers and automate the plucking of strings in several of his robotic instruments [Singer, Feddersen 2004]. He has recently created a multiple robotic musical instrument installation at the Beall Center for Art and Technology at the University of California at Irvine. It comprised over thirty new robotic musical instruments. Many of these were driven with simple stepper motors or solenoids and were percussive in nature. There were "BeaterBots, SpinnerBots, SistrumBots, RecoBots," and so on. An interesting aspect of this installation is that much of it could be controlled remotely from over the Internet [Singer, Feddersen, Bowen 2005]. More recently, he has collaborated with Paul Lerhman to create, construct, and perform a completely robotic rendition of George Antheil's famous Dadaist masterpiece, Ballet Mécanique, at the National Gallery in Washington D. C. [Lerhman, Singer 2006]. Gil Weinberg and Scott Driscoll have developed an interactive robotic percussionist which responds intelligently by listening to live human players and analyzing aspects of their playing in real-time. It will then play along in a collaborative, improvisatory manner that is based on results of the analysis [Weinberg, Driscoll 2007].

Figure 2.20 Gil Weinberg, *Haile*, Intelligent robotic percussionist.

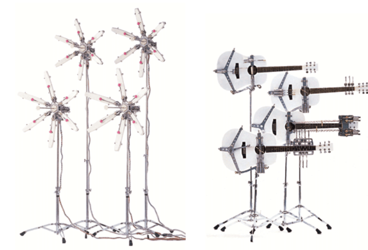


Figure 2.21 Maywa Denki, Robotic musical performance instruments. *Marimca* is an automated xylophone in the form of a flower. The flowers open when they start to play and close when they have finished. *Mecha-Folk* is a fully automated folk guitar.

In the sphere of Japanese popular music, the alternative rock group Maywa Denki has made quite an impact with their uniquely engineered musical robotics. They have invented a series of music-producing objects which are artistically ingenious and technologically very innovative. Many of the robotic objects are wearable and coordinate with the musician to automate sound creation processes. The "Tsukuba Music" was conceived to use electromagnetics and motors which produce sound by physically knocking and vibrating various materials. According to Maywa Denki, the emergence of new technologies for music generation, such as samplers, synthesizers, and computers have separated music from the material, leaving music simply as information that can only be listened to with speakers. "The Tsukuba Music was created to return our attention to music's origins, that music is created from materials" [Evans 2004].

Moving closer to the specific area of interest in this thesis, there have been a few people, though not very many, who have approached the challenge of trying to combine music creation with the invention of an artistic and engaging sculptural form. Bruce Wands [Wands 2005] introduced an interactive musical sculpture which functions as a human interface that enables participants to create their own mix of musical elements

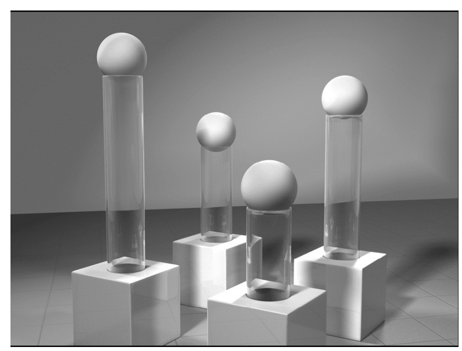


Figure 2.22 Bruce Wands, *Variations*, interactive musical sculpture installation with surrounding speakers.

which are provided. The user interacts with various sculptural elements which consists of individual modules such as a cube that contains a speaker and a tube with a removable ball that controls what musical material is heard. Many people may interact with the sculpture at the same time, and this allows for a great variety of collaborative musical experiences. Two sculptors, Daniel Rozin and Gerhard Trimpin, have created works which are, at first and primarily, sculptures, but also function as extremely unique musical instruments in their own right. It would be the work of these two artists that probably most closely associates with the intentions and ideals behind the design of the Chandelier. The robotic instrument inventor and sculptor Trimpin [Strouse 2006] moves much closer than others previously mentioned to making a particularly profound connection between physical objects and the natural musical sound that they produce. He is a major exponent and pioneer in the field of robotic musical instruments as well as sonically significant sculpture. His influence on the work of so many musical roboticists goes back for several decades. Originally connected with the seminal composer of the player piano, Conlon Nancarrow, he developed a machine to digitally translate the hole-punched rolls of player piano compositions. His interest in player pianos and the mechanization of musical instruments eventually led to an expansive tree of innovative musical robotic works. Examples of his work, such as *Der Ring* and *SHHH* celebrate the capacity of artistically designed objects to perform interesting and provocative sonic events. Trimpin has also created monumental sculptural instruments such as the high-profile centerpiece at the Experience Music Project in Seattle. This is a colossal amalgamation of hundreds of guitars and other conventional instruments which collectively produce a robotically manufactured sound that is truly unique.

Another very special work of sculpture which has, somewhat by accident, become particularly known for its anomalous

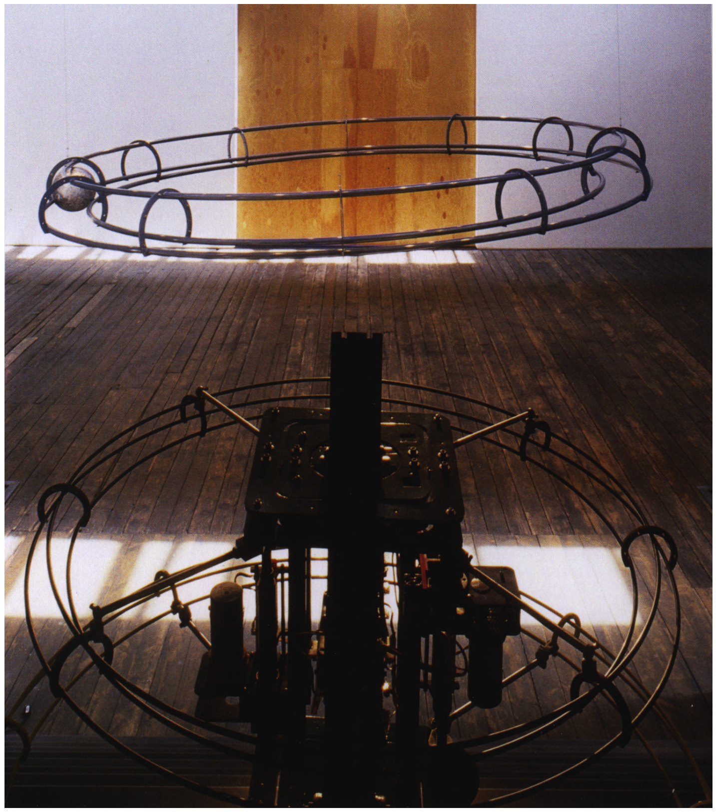


Figure 2.23 Trimpin, *SHHH: An Installation*, Sound sculpture.

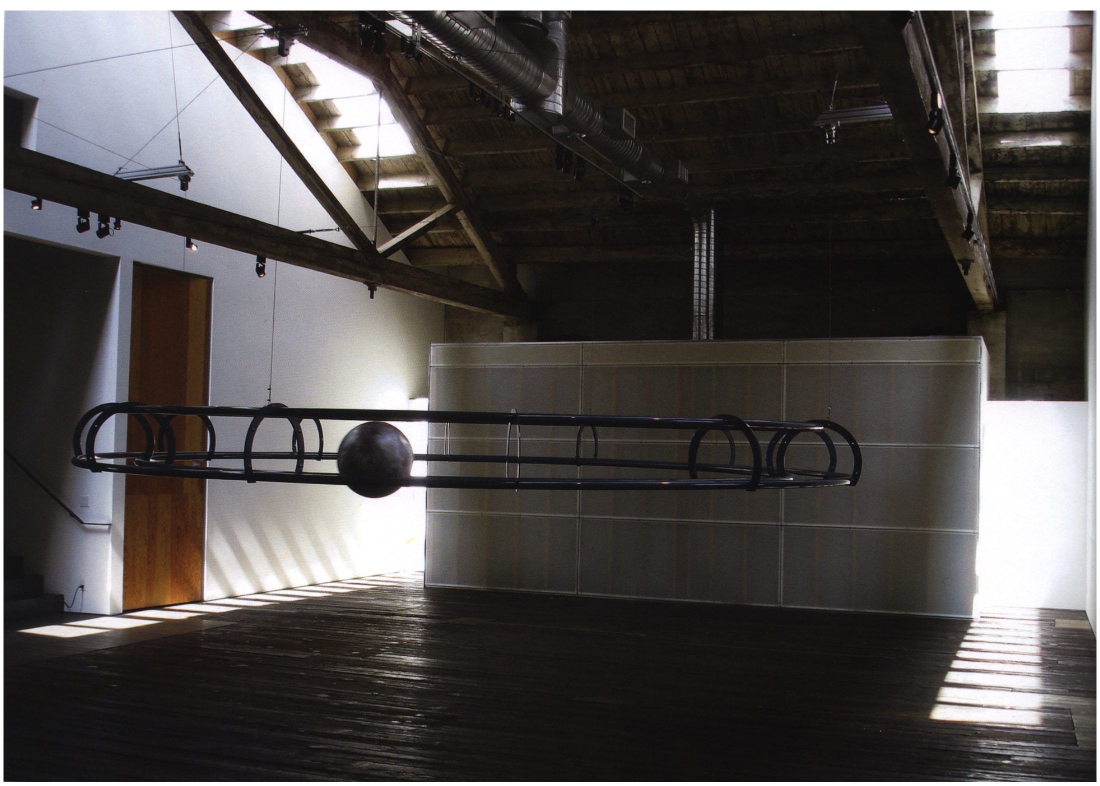
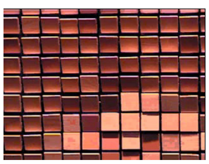


Figure 2.24 Trimpin, *SHHH: An Installation*, Suyama Space, Seattle 2006.

musical quality is Rozin's *Wooden Mirror* [Rozin 2000]. The piece is a composite of 830 pieces of wood which all fit into an octagon frame. Each piece is capable of rotating independently in order to give a visual distinction with respect to reflected light; the overall effect being that the piece as a whole becomes a pixel field which can reflect images that are fed to it through a semi-hidden camera. It is set up so that whoever or whatever is in front of it will be reflected in the image. As it turns out, the sonic effects of the moving pieces of wood and the hundreds of tiny motors which drive them are quite compelling and provide a pleasing "secondary feedback" that constitutes a kind of musical sonic image. This image echoes the visual reflection of the piece.



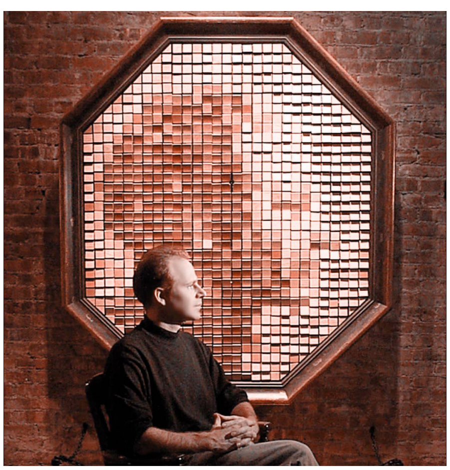


Figure 2.25 Daniel Rozin, *Wooden Mirror*, 2000.

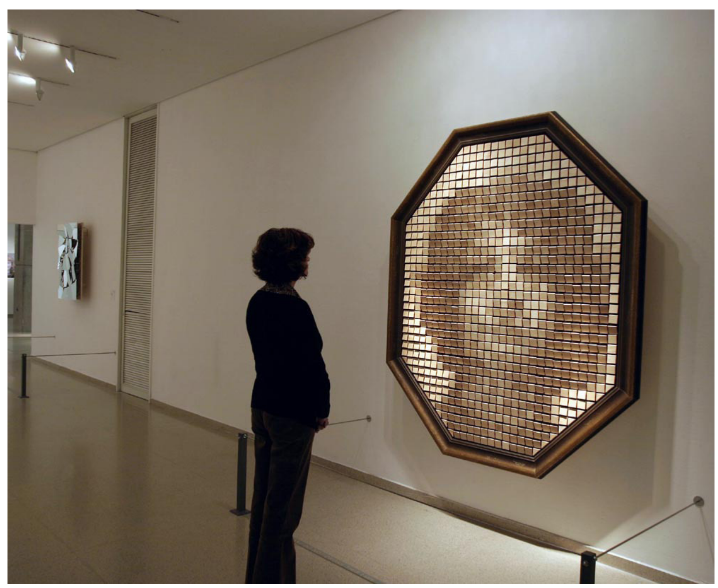
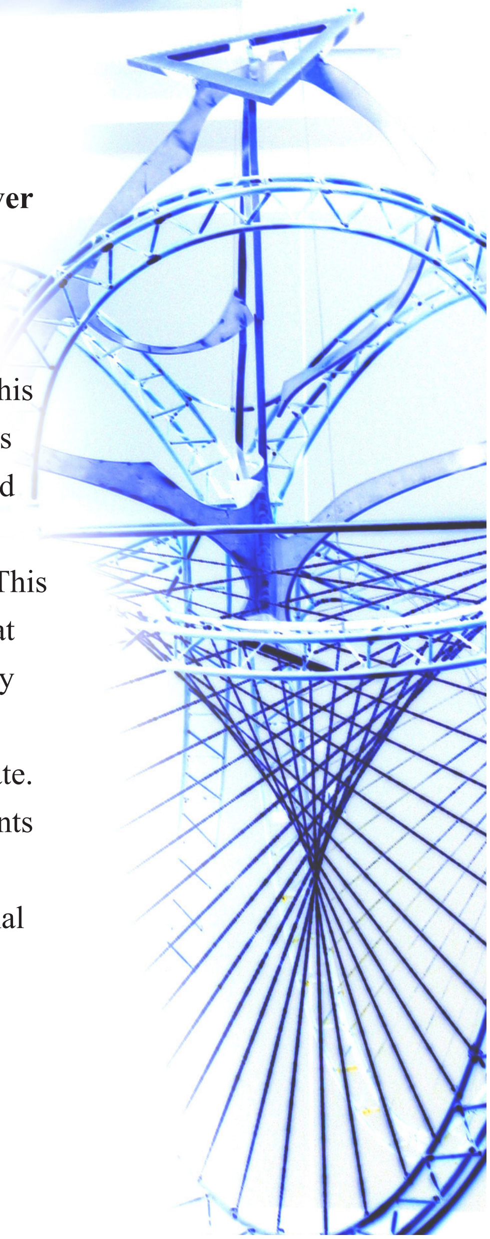


Figure 2.26 Daniel Rozin, *Wooden Mirror* Museum.

Chapter 3 Parameters of Design



3.1 Death and the Powers: An Opera by Tod Machover

The primary context and reason for the inception and development of the Chandelier is the new opera *Death and the Powers*, currently being composed by Tod Machover. This opera will be a bold venture into new ideas and technologies in set design, sound design, robotic musical instruments, and musical composition. The stage and set will represent the interior of the house of the main character, Simon Powers. This interior will eventually start to reveal itself, in subtle ways at first, as a living, breathing, conscious entity. It will gradually become apparent that it is an intelligent, interconnected "System" which will move, change shape, breath, and vibrate. Several image display surfaces and sound-producing elements will be embedded in the System, and they will show the disparate, fleeting thoughts and memories of Simon's internal world. Machover writes:

> The music of Death and the Powers will represent a bold step forward toward a new kind of opera. Innovative vocal techniques will be designed especially for this work. Instrumentation for the

opera calls for a small ensemble (ca.10 players: 5 strings, 3 winds, 1 percussion, 1 keyboard) located in the pit. Players will perform on specially designed, next generation Hyperinstruments which will represent significant advances over our current ones, in gestural sophistication, beauty of sound, and simplicity of use. Unlike current electronic instruments, these new Hyperinstruments will allow each performer to control his/her precise sound mix and balance, with overall balance of instruments and voices being modulated by the conductor. Another innovative musical feature of the opera will be the first-ever use of sonic animatronics ("sonitronics"), or physical, sculptural elements, such as a robotic "Chandelier" which is both a beautiful, compelling object as well as a subtle, resonant musical instrument whose string-like surfaces are struck, bowed, tickled and stretched by skilled Hyper-instrumentalists. [Machover 2006]

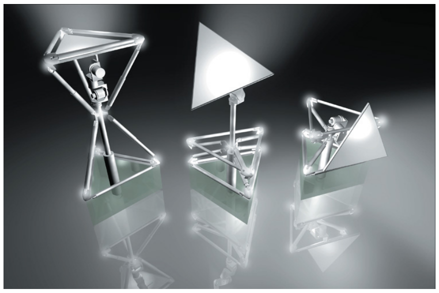


Figure 3.0 *Operabots*, animatronic elements being developed by Cynthia Breazeal's Robotic Life group, will coordinate with the Chandelier and the rest of the set to create a robotic ensemble of performance machines.

In addition to composer and creative director Tod Machover, a very diverse, world-class group of people have been involved with the design and production of this operatic odyssey of

Figure 3.1 Digital rendering of an early set design with Chandelier.

science fiction. Robert Pinsky (former United States poet laureate) wrote the libretto based on a story by Randy Weiner. The robotic environment and set pieces are being developed by Cynthia Breazeal and her team at the MIT Media Lab. Hollywood film production designer Alex McDowell (*Charlie and the Chocolate Factory, The Terminal, Minority Report, Fight Club*) will bring his considerable experience in film design and animatronics to the stage for the first time.

Figure 3.2 Digital rendering of set, Chandelier, and floating player.

To understand the full context and the raison d'être of the Chandelier, it is best to know something about the setting, characters, story, and themes of *Death and the Powers*. The basic synopsis of the opera is given by Machover:

> Simon Powers was a great man, a legend who wanted to go beyond the bounds of humanity. He was a successful inventor, businessman, and showman. During his life, he accumulated unimaginable wealth and power. He is the founder of the System, a human organism material experiment which investigated the transduction of human existence into other forms. His work was heralded as revolutionary and genius, but his ideas and experiments also had implications that mainstream society found objectionable. He has received thousands of hate letters. To many, he is considered a pariah. Reaching the end of his life, Powers faces the question of his legacy: "When I die, what remains? What will I leave behind? What can I control? What can I perpetuate?" He is now conducting the last experiment of his life. He is in the process of passing from one form of existence to another in an effort to project himself into the future. Whether or not he is actually alive is a question. Simon Powers is himself now a System. Powers must rely on his family to complete the experiment. The strains on the family come to a head, as Evvy, his third wife, withdraws

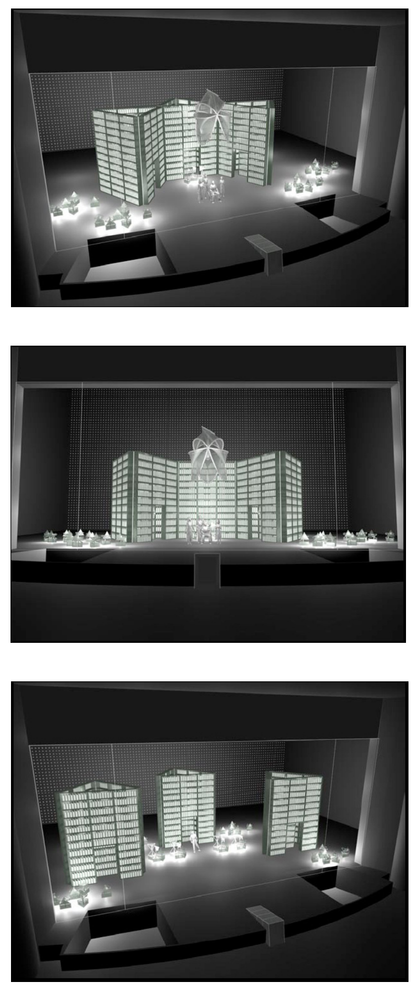
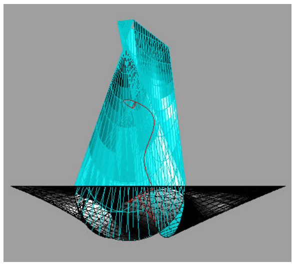
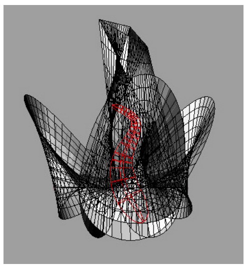
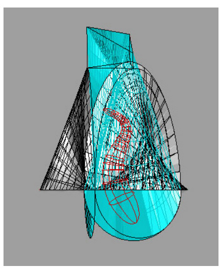


Figure 3.3 Digital renderings of the later set configurations with the final Chandelier design.







> more and more from the real world in a desire to join Simon in the System. Miranda Powers, Simon's young daughter by his first wife, is fearful of losing touch with the real world, and tries desperately to keep her father connected to the suffering of others in the world. The family also includes Nicholas, who is Simon's protégé, the son he never had. Nicholas is the ultimate product of Simon's manipulation. Nicholas holds the knowledge on how to project Simon to the future. Like a puppet and somehow incomplete himself, he is devoted to completing Simon's final experiment. Simon's transition into The System creates global havoc prompting a visit by representatives from The United Way, The United Nations, and The Administration, as well as a parade of the world's miseries— the victims of famine, torture, crime, and disease. This story is framed by a quartet of "rolling, lurching, and gliding" robots who have been commanded in some future time to perform this pageant, and who – in a Prologue and Epilogue – attempt to understand the meaning of death. [Machover 2006].

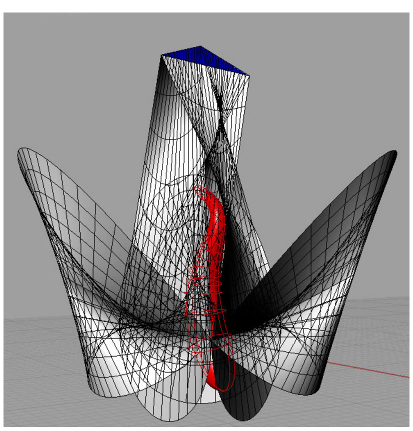


Figure 3.4 Chandelier, Early surface and wire digital sketches.

The Chandelier is the central set piece of the opera. It represents a tomb-like citadel or digital-mechanical womb in which Simon Powers is transformed and reborn into a pure state of consciousness, an alternate form of existence. Although Simon experiences a carnal death not long after the beginning of the opera, he undergoes a transfiguration into a digital consciousness and then continues to speak through a more abstract, compelling language of texturally based sound. However, the Chandelier, though central to the narrative and visual aspects of the opera, constitutes merely a part of the System which encompasses, and is embodied by, the entire set as a whole. Animatronic walls as well as a legion of robotic stage players, called "operabots" (see figure 3.0), will have an intimate coordination of motion, light, and sound within the System. In that sense, the Chandelier is not a completely separate piece, but is an integral element of the System.

3.2 Collaboration

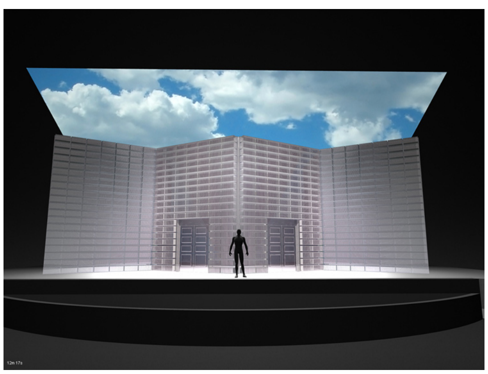
In the process of designing the Chandelier and set for *Death and the Powers*, many people have come together to participate in the conceptual ideas, artistic design, production planning, and construction strategies of every aspect of these elements of the opera. Therefore, the success of this process has greatly depended on the open exchange and collaboration of ideas between people with vastly different backgrounds. The end result of the opera production will certainly be a reflection of how effective this collaboration was.

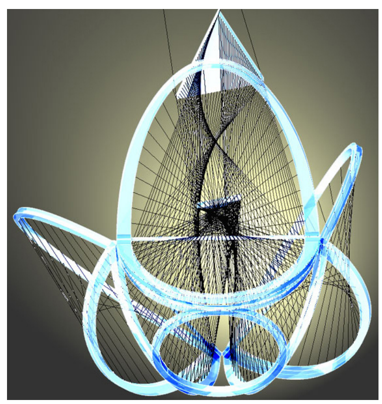
3.2.1 A True Collective Effort

Just as a large group of people have collaborated on the opera as a whole, there has been a smaller group who have taken part in the collaboration over the design and planning of the Chandelier. The three primary people who have driven the development of the design are Mike Fabio [Fabio 2007], Alex McDowell, and myself. The three of us worked extremely closely together focusing on different aspects of the design. Laird Nolan was also a very important contributor and facilitator of communications and processes. Fabio and I shared the most intimate, consistent, and on-going collaborative relationship during the entire design period. This accounts for about two years in total. Fabio's primary focus was the electromechanical system which is implemented throughout the Chandelier and is responsible for exciting the long strings of the instrument and producing unique textures of musical sound. I will touch on certain aspects of his work throughout this thesis; however, for a much more rigorous treatment of the sound production system of the Chandelier, I refer you to his thesis which addresses this particular side of the research as its central subject [Fabio 2007]. It is important to note that while my focus, and indeed the primary emphasis of this thesis, has been the design of the overall form and Fabio's focus the development of the sound producing mechanisms, the two areas have had so much crossover that they were not totally separate processes. Aside from that, Fabio had a great deal of input on the formal considerations of the design just as I have had a commensurate input on the sound creation side of things. Much of our collective research has been concerned with the integrated relationship of the two spheres.

3.2.2 A Dialogue Between Two Designers

In the earliest stages of the conceptual design phase of both the set of *Death and the Powers* as well as the Chandelier, I began having discussions with the production designer of the opera, Alex McDowell. McDowell has been a design leader in several areas of pop culture ranging from MTV videos to record jacket graphics for over 20 years. Currently, he is fully engaged as a production designer in feature films. He has worked with some of the most highly esteemed film directors such as Terry Gilliam, David Fincher, Steven Spielberg, and Tim Burton and has completed production design for such films as *The Lawnmower Man*, *The Crow*, *Fear and Loathing in Las Vegas*, *Fight Club*, *Minority Report*, and *The Terminal*. In the initial discussions, McDowell and I began to brainstorm about different formal ideas which might tie together various themes in the opera with elements in the set. This was the beginning of a long term dialogue between the two of us which would continue to take place over long distances and changing directions and the evolving design of the opera. The importance of this dialogue cannot be overemphasized. While I produced the actual formal design of the Chandelier, McDowell provided continual guidance and input about many overall design constraints which related to the larger picture of the set design. As McDowell carries with him, and is responsible for, the most fundamental design ideas of the opera, he needed to contain, in some sense, how the evolution of the Chandelier would occur. One of the most fascinating and rewarding aspects about the experience of working with McDowell was being able to observe and learn a uniquely effective collaborative design methodology. His particular sensibilities during the design process allowed him to establish a relatively open format for my own creative efforts. Then, once I had traveled a certain distance in a given direction, he would proceed to establish a corresponding design idea throughout the rest of the set. This would both contain the current ideas in the Chandelier as well as provide a fully integrated concept for the entire set design. It was a completely organic process which encouraged a design dialogue that was uniquely appropriate for the larger intentions of the opera.





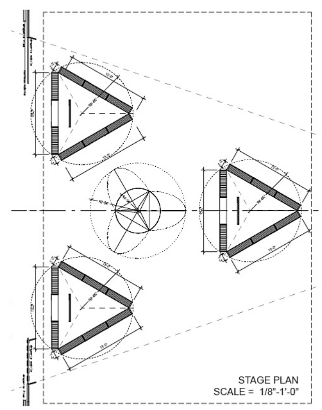


Figure 3.5 Illustration of the set scheme responding to a proposed scheme for the Chandelier. The image on the left represents an early conception of the set. The image in the middle is the Chandelier design that was introduced to the process. The image on the right shows the evolution of the set conception responding to the triangular structure of the Chandelier.

A good illustration of this process is the example given in Figure 3.5. Observe the planned configuration of the walls and surrounding set design in its initial phase. The patterns follow a kind of zig-zag order. The second image shows an iteration of the Chandelier design which was introduced to the process. The third image shows the plan drawing of a new concept for the set walls which responds to the triangular geometry of the Chandelier scheme, thus establishing a more wholly integrated, organic order for the entire scheme.

3.3 Formal Design Principles

There are several controlling principles which have factored into the formal design of the Chandelier. On the most fundamental level, there are important ideas contained in the story of *Death and the Powers,* and indeed many narrative elements, which drive the decisions about designing the form. However, the Chandelier is also a new kind of musical instrument which will be interacted with on stage by the players of the opera as both a musical instrument and a visual object which embodies Simon Powers. The constraints associated with designing a completely new kind of musical instrument also had a significant impact on the form. And finally, it is hoped that the Chandelier will, to a certain degree, function as a sculptural object with its own sense of autonomy. In this sense, there are several principles driving the design which relate more to purely sculptural considerations. This is because, in the end, the Chandelier is a powerful visual object which is central to the overall scenic landscape of the opera.

3.3.1 Narrative Ideas Controlling Form

Many narrative elements can be drawn from the *Death and the Powers* story and translated into visual metaphor. In developing the design of the Chandelier, there were certain ideas in the narrative which demanded to be present in its form. As the main character, Simon Powers undergoes the death of the body. He is then soon resurrected through being transformed into the System which is represented by the large walls of the set as well as the Chandelier which occupies a large visual space above the center of the stage.

Since the idea of rebirth and resurrection becomes such a dominant narrative theme in the opera, it became a dominant force in driving the form of the Chandelier. Throughout all of the iterations of the design, this is maybe the single most pervasive and consistent idea which remains embodied in the form. Visually, the Chandelier contains a three-dimensional abstraction of an egg like shape. There is a large, centralized volume of an egg that is implied spatially by the metal structural elements which envelop the space. Even though the entire piece will change shape through the movement of its three large constituent wings, the egg metaphor is always present. There is also the notion of womb which is visually present, though quite abstracted. In the final iterations, the center of the piece is enclosed and “protected” by the overlapping layers of strings and other structure. Yet, the fine lace-like filigree of the metal structure and the twisted sheet-like layers of long strings impart a quality of transparency which allows the center to almost glow through these layers as a life force within a womb.

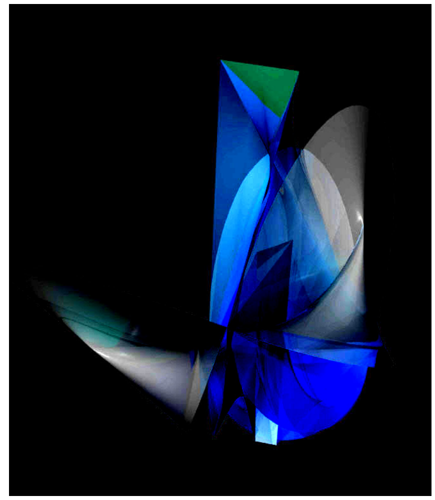


Figure 3.6 Abstracted composition study of the Chandelier.

In the *Death and the Powers* story, the theme of Simon’s death is partnered with birth and is also a duality which gets embodied within the Chandelier. One can visually identify a tomb as well as the womb idea. The tetrahedron, one of the five Platonic solids, has often been identified with Egyptian tombs. It is also the simplest enclosed geometric volume that is known. Much of physical creation is based on the tetrahedron [Field 1988]. It has four sides, each of which is an equilateral triangle. Johannes Kepler associates this volume to the element of fire. Fire is associated with inspiration and passion. It is structurally the strongest volume of all the Platonic solids. [Kepler 1981]. Beginning somewhere in the middle iterations of the Chandelier design, the 3D design sketches start to incorporate a tetrahedral body as well as an egg volume. Both the tetrahedron and the egg formally continue their presence throughout the rest of the design progression until the final version.

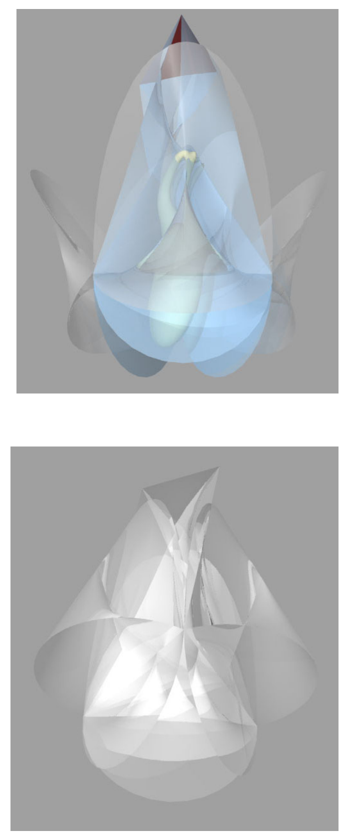


Figure 3.7 Digital studies of surfaces and light, Chandelier.

Metamorphosis becomes another theme which gets embodied

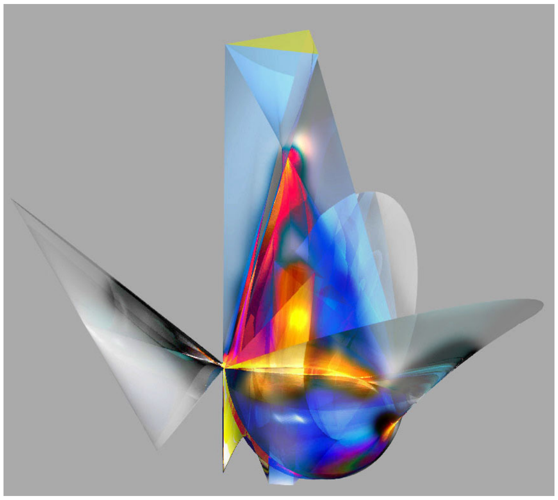


Figure 3.8 Digital sketch of the 'metamorphosis' concept, Chandelier.

in the Chandelier piece. Simon Powers, in effect, undergoes a virtual metamorphosis during the transformation from his corporal death into the System. The System itself gradually becomes an evolving form with organic changes that indicate a life entity, and just as we observe the metamorphosis in many Earthly life forms, the same will be seen in the System. Therefore, much of the thought about how the Chandelier would actually change form relates directly to an electromechanical metaphor of this notion. However, as I will elaborate further in section 3.4, when trying to design a performance piece of this size and weight on an opera stage where there will be many people present interacting with the set, there are considerable restrictions and difficulties associated with attempting to have the piece completely change shape by a purely mechanical means. Therefore, an alternative approach which involves dynamic illumination and the interplay between light and surfaces of the internal shapes has been used to give the sense of metamorphosis.

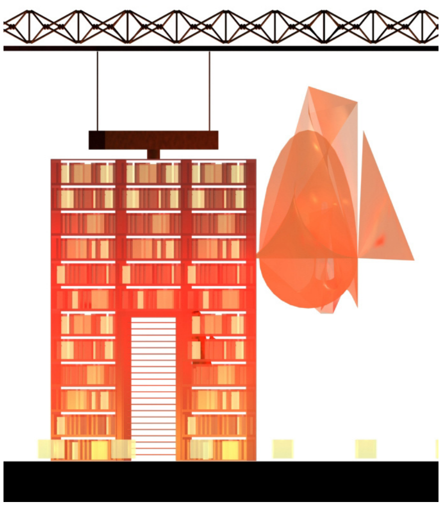


Figure 3.9 Set elevation showing scaffolding above.

Another component of the narrative from the *Death and the Powers* story is the fact that the System is actually in development. It is not fully complete and is therefore a part of an ongoing experiment which continues to be mysterious and unpredictable. McDowell shows the System in development with the use of a visually exposed scaffolding structure, some of which might be more finished in its look than other sections. This was also an important visual element in the Chandelier. Having the open truss look in the external structural frame accomplished two things. It gives the sense that even the Chandelier piece is still somewhat under construction as the System, as a whole, is developing; and it also allows for a crucial visual transparency throughout the piece, so that the layers of intermeshing strings as well as the central organic form can be perceived and appreciated.

Figure 3.10 Illustration of the "under construction" aesthetic, Chandelier.

I need only mention that there is the almost ubiquitous idea of consciousness, and perhaps more precisely, altered consciousness which continually imbues the story of the opera. This becomes a primary theme working in the opera. Much of Simon Power's character is developed through the act of questioning the very nature of his consciousness and existence. The design of the set, which embodies the System, incorporates many visual and sonic devices to convey a powerful sense of altered consciousness. The Chandelier piece also perpetuates altered consciousness through the movement of directed light, the coordinated mechanical rotational movements of the "wing" sections, as well as a virtually infinite number of highly intricate moiré patterns that are produced from the complex visual interferences of the string layers.

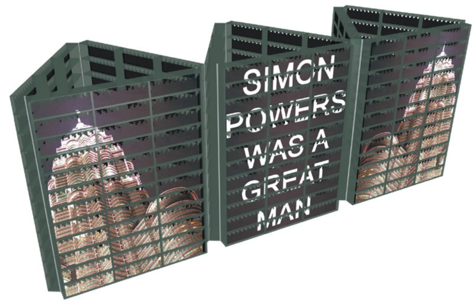


Figure 3.11 Digital rendering of the display graphics embedded in the set walls.

3.3.2 The Influence of Other Art

Any artistic production will typically borrow a great deal of conceptual material from other sources including works of literature, philosophy, science, architecture, and other artists from the fine arts. In the initial brainstorming sessions with the composer (Tod Machover), director (Diane Paulus), and production designer (Alex McDowell) of *Death and the Powers*, all of the primary narrative and thematic ideas were brought together and discussed extensively. Soon, McDowell was able to make useful and interesting connections with other work and figures in the greater world of the visual arts. He saw significant parallels between many of the discussed ideas in the opera and the work of certain artists such as Naum Gabo, Louise Nevelson, Rachel Whiteread, Antony Gormley, Constantin Brâncuşi, and Henri Gaudier-Brzeska to name a few. The work of these artists has provided a massive influence on the visual thinking which has been applied to the entire opera set design.

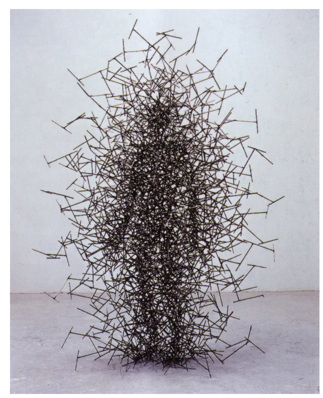


Figure 3.12 Anthony Gormley, *Quantum Cloud XVI*, 2000.

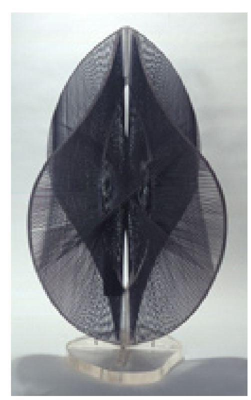


Figure 3.13 Naum Gabo, *Linear Construction II*, 1951.

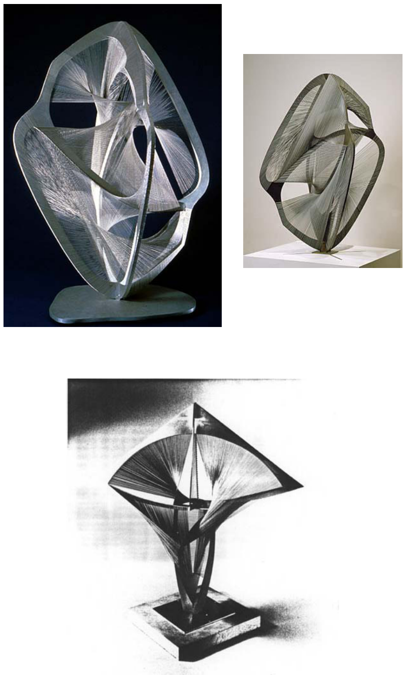


Figure 3.14 Naum Gabo, Sculptures: *Linear Construction* series.

Figure 3.15 Rachel Whiteread, *House*, Cast 'negative-space' of a house 1993.

Figure 3.16 Rachel Whiteread, *Twenty-five spaces* 1995.

There were certain artists whose influence provided a particularly strong inspiration for the design of the Chandelier. The work of Naum Gabo played an obvious and vital part in the formal ideas of the piece. This pioneering Constructivist sculptor used materials such as glass, plastic, and metal to create a sense of spatial movement. He created evocative, geometric sculptural works where curves replaced angles in new kinds of spatial constructions made out of taut wire and plastic thread. One of the really amazing qualities that is observed in these wired constructions are the highly complex moiré effects which are produced through layers of geometric arrays of strings visually interfering with each other. This visual idea became a primary design force in the formation of the Chandelier. The effect of the moiré patterns from the interference of string arrays gives a fascinating and dynamic sense of movement when the arrays are in motion against each other, even if that motion is quite simple and slow. This opportunity for such dynamic movement is utilized in similar constructions of moiré patterns within the Chandelier.

The work of Rachel Whiteread conjures up notions of timeless archeological ruins yet imbued with an austere brand of modernity through her unique heavy-cast sculptural works. She is widely known for her forays into massive and voluminous sculpture of negative spaces. These works are often casts of ordinary domestic objects, and in numerous cases, the space the objects do not inhabit, which instead produces a solid cast of where the space within a container would be; particular parts of rooms, the area underneath furniture, as examples. "Denatured by transformation, things turn strange here. Fireplaces bulge outwards from the walls of House, doorknobs are rounded hollows. Architraves have become chiselled incisions running around the monument, forms as mysterious as the hieroglyphs on Egyptian tombs." [Muir 2001]

The concept of "negative space" has always been extremely important in the visual arts. It essentially means that the artist or observer may change his/her visual focus to the shape and contour of the space between and surrounding the material matter of an object or objects. One can almost envision a materiality and a sense of space as solid mass which then has the effect of reversing the perception of what is mass and what is space within a given view of something. All visual artists make frequent use of this notion to help them construct visual compositions as well as to see proportion and relationships of objects more accurately.

Figure 3.17 Rachel Whiteread, *Untitled (Stacks)* 1999.

On a philosophical level, "negative space" can be understood in connection with the idea of ambiguity, and in this sense, the nature of Simon Powers' very existence is utterly ambiguous. Therefore, ambiguity and negative space become ideas that get manifested throughout the set design. The high walls of the set have a large number of repeated rectilinear elements which are laid out in a continuous grid-like arrangement. The reading of these elements is, in itself, ambiguous. They can be read as books on a moving cascade of shelves which form part of the interior of Simon Powers' house. However, these wall elements are also a vital part of the System which contains Simon's consciousness. With this in mind, the elements can be understood as a great network of digital bits that store the components of intelligence and memory which reside in the System. The Chandelier also deals with negative space and ambiguity in its form. As it rotates and moves its wing sections, the moiré patterns and string densities change shape and transparency; and as a consequence of this, the sense of where space and mass are bounded to construct the overall form of the piece becomes ambiguous.

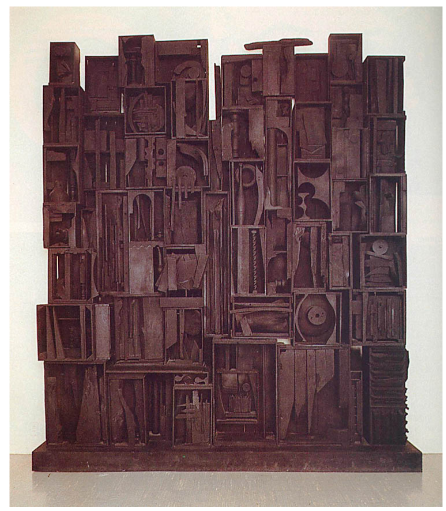


Figure 3.18 Louise Nevelson, *Sky Cathedral* 1958.

Constantin Brâncuşi was a Romanian sculptor who worked in Rodin's workshop. He created simple, geometrical, and sparse objects which were highly abstracted, non-literal representations of his subjects. His drive was to depict "not the

Figure 3.19 Constantin Brâncuşi, *Bird in Space* series circa 1925.

outer form but the idea, the essence of things." [Brezianu, Geist 1965] His "Bird" series sculptural work conveys a strong sense of flight and motion as well as a sense of fleeting, transitory, ephemeral life. These intellections also frame Simon Powers' existence, as it is in any one form, transitory, and they have a significant impact on the Chandelier design. The "bird" and "flight" themes are probably the most obvious of any other source of inspiration.

3.3.3 Design of the Set

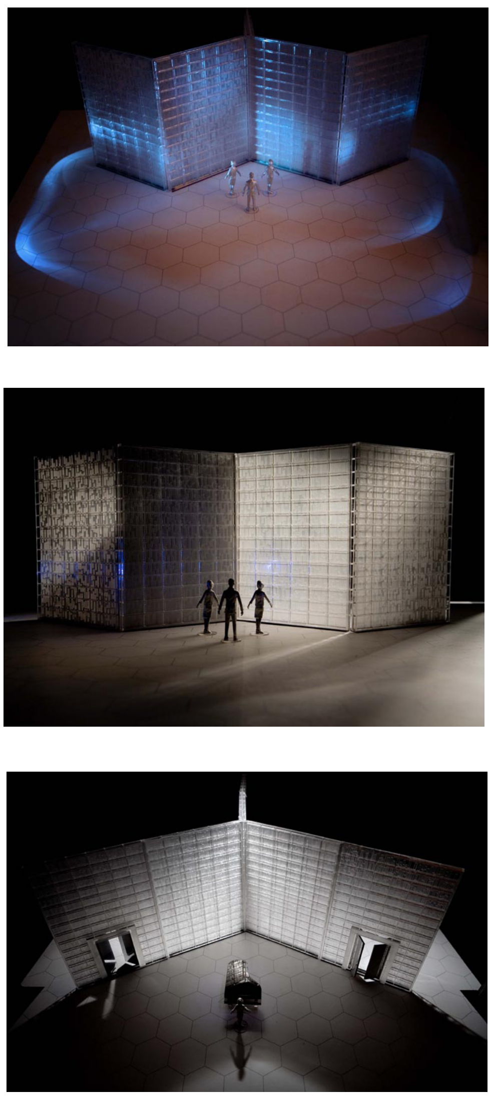


Figure 3.20 Early set design physical model, Laser-cut acrylic.

The set design for the *Death and the Powers* opera started with large twenty foot walls which were designed to rotate and move around the stage and proscenium. The ability to move and reposition themselves through robotic action allows a multiplicity of varying architectural environments and geometric configurations. These configurations represent the thoughts, emotions, and communications of Simon Powers since they are actually encompassed by the System. However, the set walls should not be understood as separate from the Chandelier piece. Together, these components make up the System, and the Chandelier will continually be coordinating with, and relating to, what the set walls are doing in a unique choreography of objects which might be thought of as a kind of slow-motion dance of performing objects.

Each wall stands about twenty feet in height and contains vertical, rectilinear elements which are intended to make a very simple one-axis lateral movement in the perpendicular, outward direction with respect to the plane of the wall. Despite the simplicity of movement that each element would have, when the number of such elements are multiplied to articulate several large wall arrays, the possibilities for very interesting, evocative, and coordinated, global pattern events become quite exciting. The movements and behavior of these arrays can be choreographed to create dynamically changing shapes that can give a sense of physical being and life to the entire set as a single entity, the System.

As previously mentioned, each cell or element making up the set walls can be understood both as a digital element of a large intelligent matrix or a book in an endless library of Simon Powers. In developing the initial forms of the walls, I used various thicknesses and sizes of acrylic sheet material, and cut, etched, and formed it with a laser cutter to construct a half-inch scale model of the set. The work of Rachel Whiteread and Louise Nevelson had quite an influence on our thinking about the look and feel of the walls. Nevelson's abstract expressionist "box" sculptures convey a strong sense of compartmentalization and something of a chaotic yet structured order. Whiteread's cast bookshelves allude heavily to molded form. I tried to work these notions into the wall designs. The final result of the wall has a very interesting and close association with the Hal 9000 computer character in Stanley Kubrick's 1968 film *2001: A Space Odyssey*. The internal structure of Hal's brain closely resembles the look of Simon Power's brain, the System, in that there are vertical, rectilinear cell elements that move in and out of a large wall array. This obvious parallel may or may not have been intended.

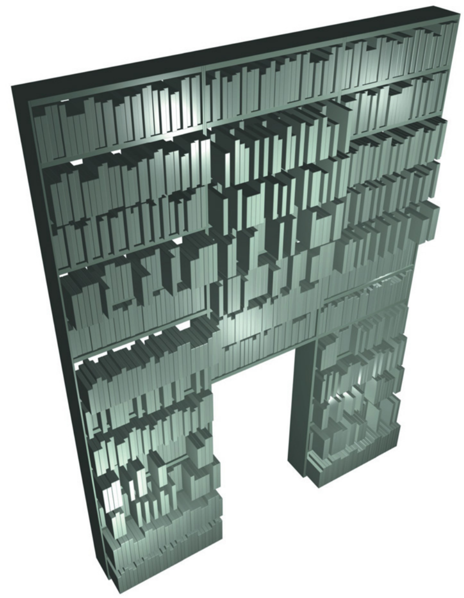


Figure 3.21 Digital rendering detail of set wall.

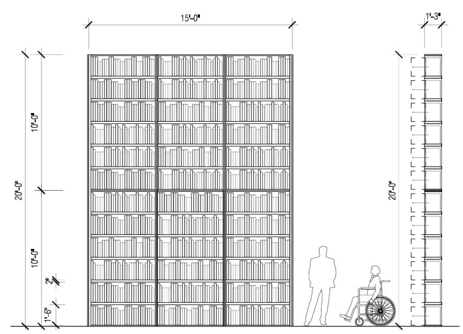


Figure 3.22 Set wall elevation drawing (drawn by Arjuna Imel).

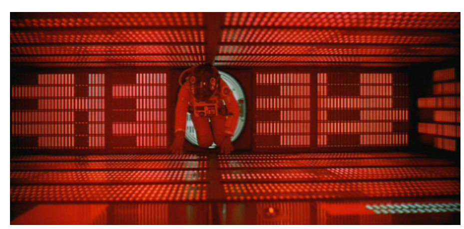


Figure 3.23 Inside the "brain" of Hal 9000 from *2001: A Space Odyssey* 1968.

3.3.4 The Chandelier as a Musical Instrument

The Chandelier piece represents many things in the *Death and the Powers* opera and it serves multiple functions. However, perhaps the most significant function of the piece is that it is a kind of newly invented and engineered musical instrument. It is intended to be played by both the opera players on the stage as well as other off-stage performers who will be able to control the creation of musical sound from a remote interface such as a keyboard or other physical controller device.

One particularly novel musical feature of the opera will be the invention and use of sonic animatronics or "sonitronics" which are being defined as beautiful, compelling sculptural objects that will have a physical means to produce and perform music [Machover 2006]. The Chandelier piece will be one of the largest, most elaborate, and most significant sonitronic machines of the opera. It is an instrument that will produce a wide range of timbre variations through the subtle interference action and sympathetic resonances of the many layers (virtual surfaces) of long strings. The strings will be excited by a large collection of rotating actuator motors which are equipped to stimulate resonant and vibrating action in the strings by several methods. There is also a set of electromagnets which will directly stimulate the strings through a strong, localized electromagnetic field reproducing audio information which is fed to the magnet. There is also a set of magnetically driven hammers which strike the strings much like the key-hammers of a piano [Fabio 2007].

As a musical instrument, the Chandelier is quite unique. There exists no other musical instrument which compares to it. While there are piano strings being stretched between a series of metal frames, the way that the strings are used to produce sound in the Chandelier is profoundly different. At moments, the piece may start to resemble a harp, but again, the way that a harp works to produce sound from the direct plucking of the fingers is fundamentally different. In our initial discussions about the design of a new musical instrument, Fabio and I explored concepts of instruments with many long strings. We became fascinated with the possibilities of a large number of strings that could interact with each other through sympathetic resonances, due to the close proximity that the strings would have, as well as the complex timbres that would result from other strings that would physically interfere by crossing each other and transferring a proportion of the resonant motions.

Collectively, the many surfaces[1] of strings interacting together as a whole would theoretically produce an extremely rich and complex range of timbres. And the sonic result would tend toward highly resonant, droning sounds that could vary dramatically in timbre. Thus, this new kind of instrument would emphasize a scale of changes in texture or timbre rather than a conventional emphasis in a scale of pitches where the basic timbre remains relatively fixed.

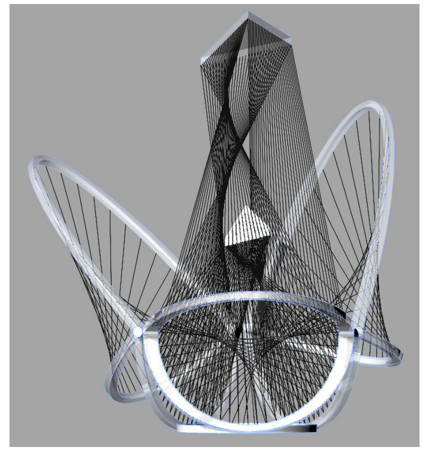


Figure 3.24 Chandelier iteration: Showing the interference patterns of the string surfaces.

With this in mind, I began to work with large arc shapes that would give a vague visual impression of a fan-like or wing arrangement to the strings. This was at once reminiscent of the sculptural work of Gabo and formally appropriate for what we were intending to achieve sonically with crossed and sympathetic strings. The parabolic arc shapes also provided a sufficient spatial layout of the strings in order to accommodate the actuator hardware that would excite the strings. There was another reason for the parabolic geometry. One only needs to make a cursory analysis of conventional musical instruments to find that there is a great deal of canonic geometry and even symmetry consistently posited in the designs. This is related to the physics of construction and the acoustic properties of these instruments which demand canonic geometrical form [Fletcher, Rossing 1998]. Although there was not any rigorous acoustic analysis or specific rationale for the parabolic geometry, there was, nevertheless, a strong intuition about the inherent physical benefits of canonic and symmetrical geometry in stringed musical instruments that guided the decision to incorporate some amount of it in the Chandelier structure.

Figure 3.25 Traditional musical instrument examples which illustrate canonic geometry and symmetry.

3.3.5 The Chandelier as a Kinetic Sculpture

Much of the thinking that went into the design of the Chandelier established certain principles that are related only to

1 The use of the term 'Surface,' in this context, intends the implied, ruled surface that a succession of strings articulates.

sculptural considerations.

> Form, whatever the means of expression, always must be understood in connection with space. And this so-called embracing "concavity"—and why not embraced "convexity" as well—is nothing else than the sphere of light, shadow, and atmospheric effects within which form must be conceived, and within which form exerts its influence. [Saarinen 1948]

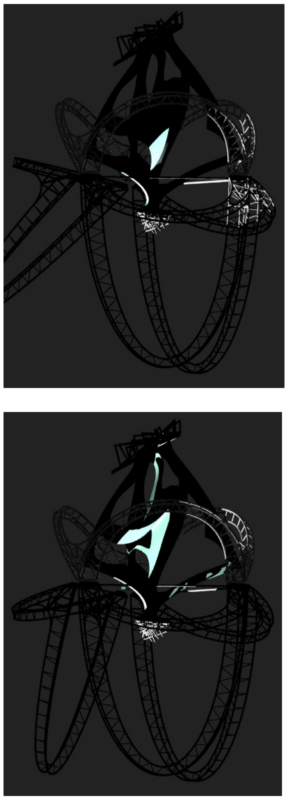
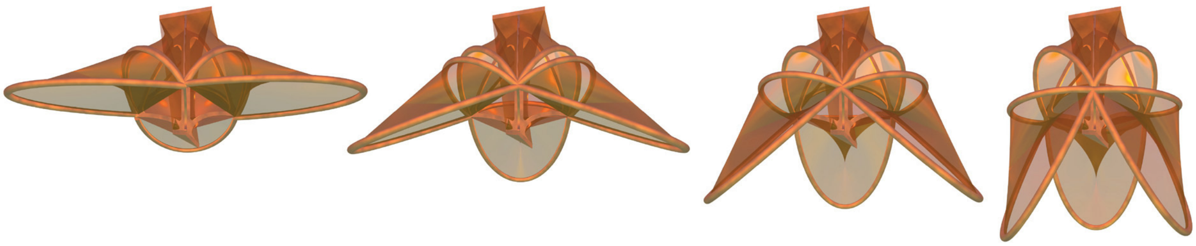


Figure 3.26 Spot-light studies of the Chandelier showing the visual changes in shape.

In his famous treatise, *The Search for Form in Art*, the legendary architect Eliel Saarinen encapsulates an idea in the preceding quote that is central to much of what has driven this thesis. Form simply cannot be perceived, much less understood, apart from the visual effects of light and shadow. As Saarinen would seem to indicate, reflected light, for all intents and purposes, is form de facto as far as our eyes are concerned. A good example of this would be if one considers the Moon in its typical appearance which is a crescent most of the time. Children will simply accept that the Moon has the shape of a crescent, and it is only because of our scientific knowledge of planetary bodies that we understand it to be a sphere and not a body that changes shape through the month.

In conceiving the design of the Chandelier, movement of the form has continued to be of primary interest for the purpose of enabling such an important, vital piece of the System to maximize its ability to function as an object of expression and performance. It is clearly a kinetic sculpture as a result of the three wing sections which are each able to rotate through a 90-degree arc independently. There are several positions through the 90-degree range that seem to "lock" into place as a result of certain visual alignments of both the metal structure and the patterns created by the surface layers of strings (see Figure 3.27). This imparts an apparent ability to be able to change shape, which alludes to the notion of metamorphosis. But the kinetic quality of the piece is extended much further through the specifically designed relationship between directed illumination and shaped surfaces. This is implemented as an integral aspect of the formal design. As described later in Section 4.4, light sources can be attached to the tip of



the wing sections and directed toward the center form. As a consequence, when the wing sections move, the illumination will change the apparent mass, contour, and shape of the center. This will greatly enhance and extend the perceived kinetic behavior of the Chandelier sculpture.

Figure 3.27 Positional changes of the Chandelier. The first and last positions visually “lock” into a new shape.

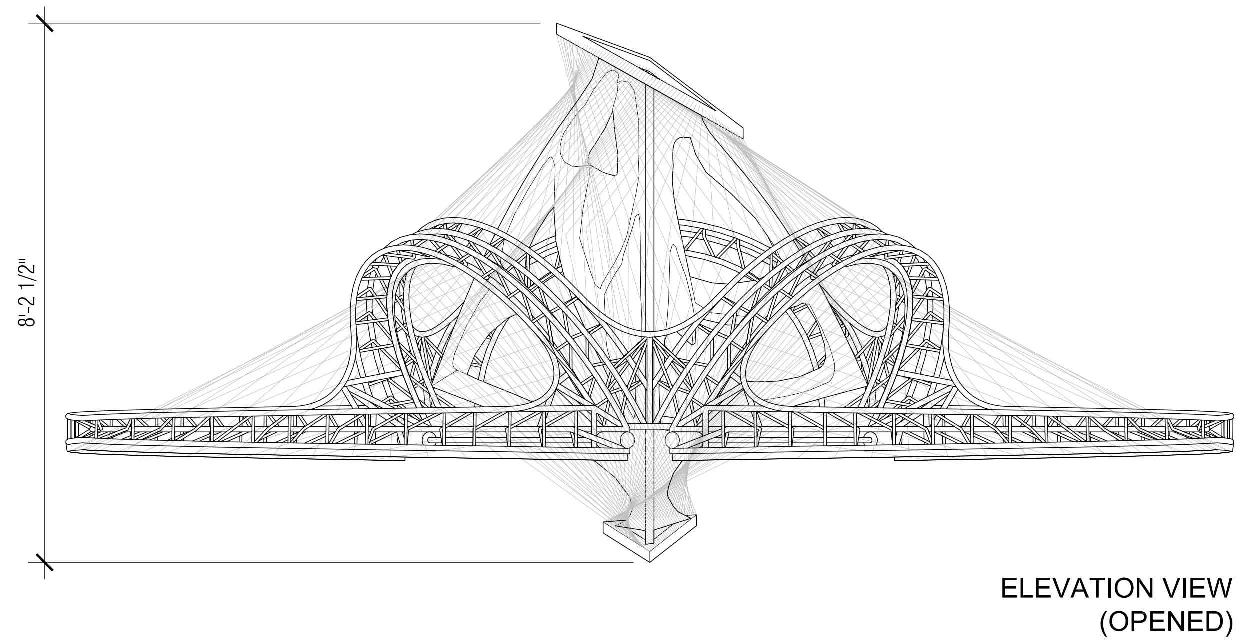
3.4 Mechanical Design Principles

Along with the formal design principles previously discussed, there are several mechanical design considerations that have factored into the Chandelier. With the implementation of such a large number of strings, roughly 270, all of which will require enough tension to adequately enable the production of sound, the collective tensile forces will transfer to the metal frame structure and produce a torsion upon the frame that must be addressed. Decisions were factored in about what materials would be appropriate to deal with such forces, aside from the purely aesthetic considerations about material. The solution to the problem of engineering the movement of the wing sections became a primary mechanical principle impacting the design. Finally, the engineering of the electromechanical system to produce sound would have to be integrated with the form.

3.4.1 Forces, Tensions, and Tectonics

The most immediate problem concerning the internal physical forces acting on the Chandelier was the torsion imposed on the supporting metal structure. This would be as a direct result of the several hundred piano-wire strings which form the implicit ruled surfaces all around the entire piece. Presumably, the strings would have to be tensioned enough so that they would function effectively as vibrating, resonating sources of sound. In a piano, the total tensile forces of the strings amount to a sum that is in the thousands of Newtons (equivalent to more than a ton). For that reason, the piano requires a very heavy cast iron frame to support such tensile forces. However, to even consider having anything close to that amount of overall tension in the strings of the Chandelier was simply not an option. One of the more important design priorities for the Chandelier was to insure a high degree of transparency throughout the entire piece. This was essential in order to maximize the rich, visual perception of the multiple layers of strings and reflected light. If we were to engineer enough supporting structure to accommodate the kind of tensile forces found in a piano, the piece would almost have to be a solid

Figure 3.28 Elevation drawing of the “open” position of the Chandelier (drawn by Arjuna Imel).



mass of steel, or at the very least, there would have to be an unacceptable amount of metal structure. This, of course, would prevent the desired transparency as well as create a very tenuous safety hazard with the suspension of such a heavy mass.

It was decided that the most desirable visual quality of the Chandelier should be that of transparency; and in order to maximize this, the structural metal support system would need to have the least amount of mass as could be possible. At that point, we began working with lattice-like, filigreed,

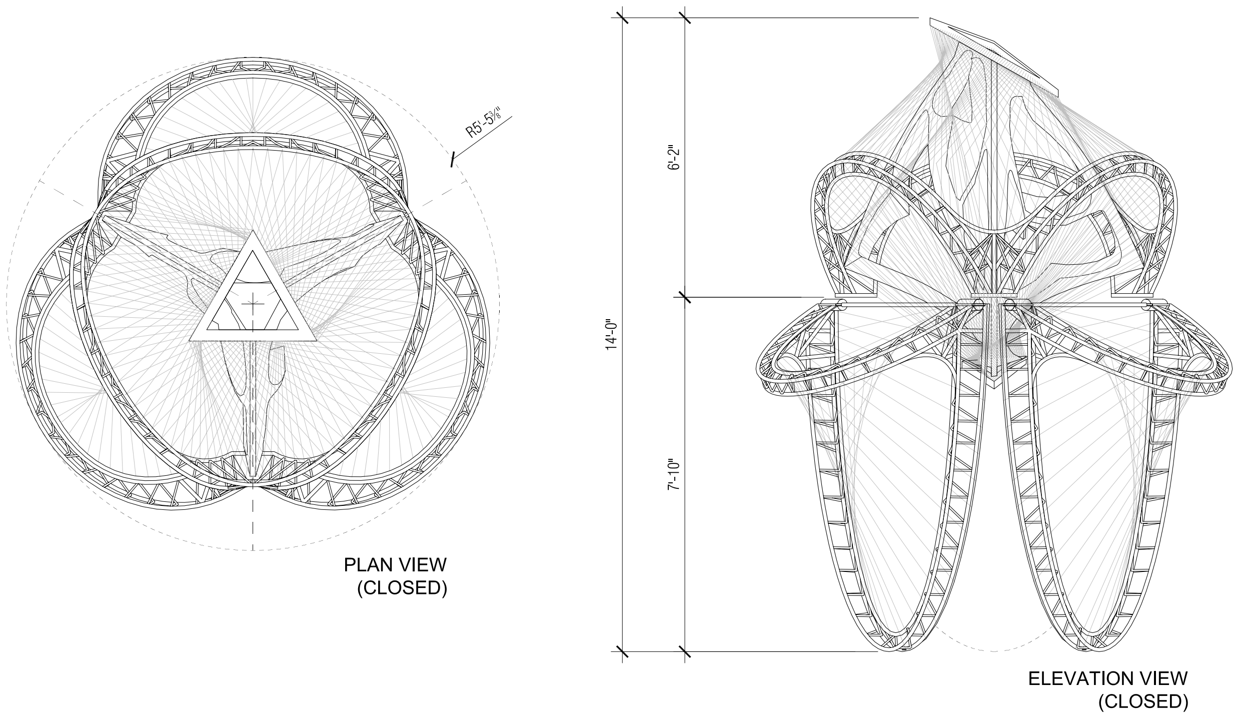


Figure 3.29 Plan and elevation drawings of the “closed” position of the Chandelier (drawn by Arjuna Imel).

and modestly sized structural forms. Therefore, it also became clear that the tension used in our strings would have to be significantly less than that used in a piano, despite the fact that we were experimenting with piano wire. There was also the notion that only a few of the strings would actually have to be used for direct sound creation. This would certainly lessen the overall tension in the piece, because the remaining strings could be installed with much less tension in them.

Nevertheless, there will still be a significant torque imposed on the outer cage structure as well as the central skeletal structure which connects directly to the triangular hubs at the top and bottom of the final design. Only a structural engineering consultant can do a complete analysis of the stresses and strains in the proposed design of the piece, but we are confident that our structural intuition has allowed for enough strength in the currently designed structure.

The other major issue of structural concern are the three primary points of convergence in the structural frame (see Figure 3.29). These three points form an equilateral triangle with each other, and each is a meeting place for two segments of the main frame, two corners of the wing sections, and a primary bearing point of the central form. Each of the three points is also a support point for suspending the entire Chandelier instrument. In accommodating this highly dense, tectonic condition, we introduced a relatively thick bearing plate to accept all of the structural chord members flowing into the point. The aesthetic is akin to a kind of spider web scaffolding which is in line with the theme of the System being under construction.

3.4.2 Material Considerations

The question of which materials to use to construct the Chandelier comes down to both aesthetic as well as mechanical issues. With regard to the components of the surrounding structural frame, the primary concern is the weight that would accumulate with a very heavy material. Because of the demands for a certain degree of strength and structural rigidity, it seemed clear that the requirements were dictating that it be made of metal, especially in light of the modest, delicate size of the members. However, to control the weight, the most feasible type of metal would have to be aluminum. This metal also possesses a desirable finish that reasonably satisfied the aesthetic desires which we had for the piece.

The major requirement for the strings was that they also had to be strong enough to withstand the tension imposed on them, even though we had determined that it wasn't going to be anything close to that of a piano. Incidentally, given that the frequency produced from a vibrating string is directly proportional to the tension within it, the frequencies with which we were working came to be much lower than the intended frequency range for the piano wire that we were using. It became clear after the construction of the physical prototype model that the strings would need to have a shiny and adequately reflective finish in order to have a visible presence at the distances required during a performance. As it turns out, the relatively minute diameter (approximately 1.5 mm) of the strings is not so much of a factor visually, as we had feared. Rather, it is their ability to reflect light that matters most.

Figure 3.30 Close-up of the Chandelier wing showing the reflective qualities of the strings.

The material that could be used in the central form will ultimately have to be decided at a later point in time. There was not enough time to experiment with an actual full-scale model of this piece. Hence, the possibilities for what the material could be are very wide in range. I envision an anodized sheet metal with an opaque, matt finish to be used for the surfaces of the central form. That would allow for a very interesting and evocative interaction with the mounted spot-lights on the wing sections.

3.4.3 Principles of Movement

One of the more challenging problems in the development of the Chandelier was the strategy for how the piece might move and change shape. The greatest obstacle to overcome was the fact that several layers of tensioned strings would naturally depend on static structures to hold and stabilize their tension. This was a basic conflict. If the structural requirements of a sculptural musical instrument were based on the need for stability in reproducing sound, how could the very structure that provided that stability be capable of motion or the extended idea of changing shape? This proved to be too difficult of an engineering problem to deal with in a reasonable amount of time.

The solution that I have proposed answers the challenge with a combination of simple rotational movements given to three sections called the "wings," and an interaction between the highly surface oriented central form and theatrical spot-lights which are a part of the wing assemblies. The result is that as the wing sections rotate independently to change the global form of the Chandelier, the lights mounted at the tips, which move with them, visually change the shape of the central form. This overcomes the nearly impossible problem of trying to create a visual metamorphosis entirely through mechanical means. A study of this visual effect is presented in Section 4.4. There was also another visual dimension which would add significantly to the sense of movement beyond just the simple rotation of each wing section. As the wings move even slightly, there is a vibrant and active moiré effect happening with the visual interference of the string-layers, and the more layers that overlap in the observer's line of sight, the more depth and energy there is in the effect.

The simple rotational movement of the wing sections required a drive system to control that movement. It was highly desired that we would keep as much of the electromechanical apparatus out of the main envelope of the Chandelier piece itself. Therefore, we proposed a motorized system that would control the wing sections using cables from above. The 1/4 size physical model built from the 3D CAD design implemented such a system, and the results seemed to be an adequate proof of concept.

3.4.4 Principles of the System to Produce Sound

In this section, I will focus only on a couple of general principles which guided the Chandelier as a musical instrument specifically as they relate to the overall form. A more detailed explanation of the sound production system is given in Section 4.7. As mentioned, a more thorough investigation of this system, and its engineering, may be found in Fabio's thesis [Fabio 2007].

After the basic mechanical ideas for producing sound in the strings had been established, we began to formulate strategies for how the form of the Chandelier could work with those

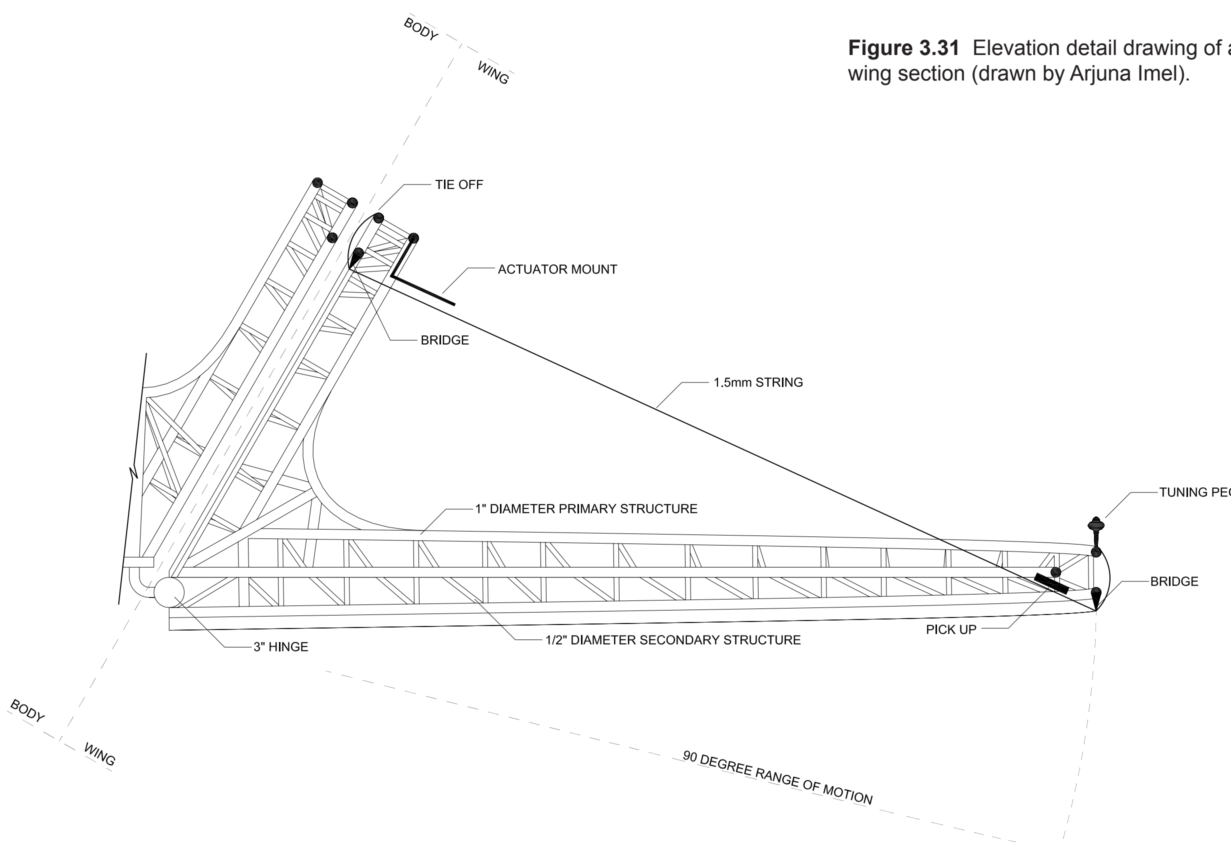
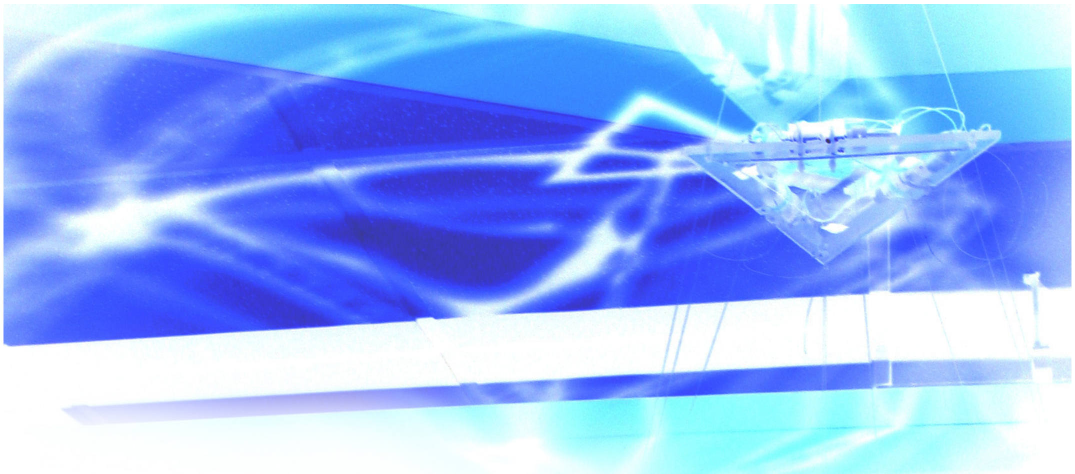


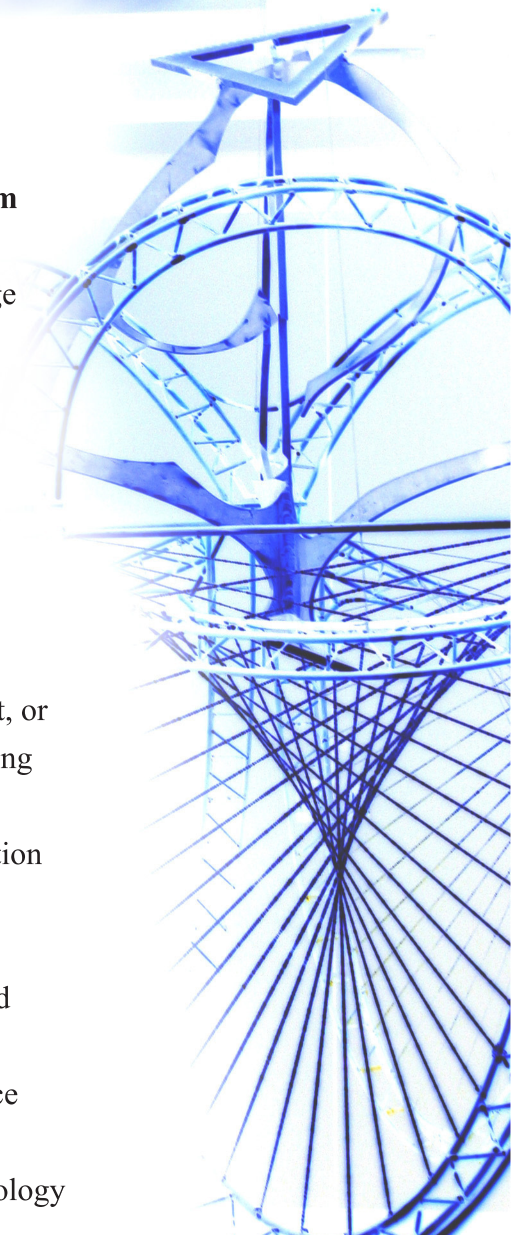
Figure 3.31 Elevation detail drawing of a wing section (drawn by Arjuna Imel).

ideas. It was decided that the mechanical components of the system would comprise motors and actuators that would excite or interact with the strings in some way. What developed from Fabio's work was a series of modules that required that they be installed within two or three inches of their respective strings. There were also guitar pick-up modules which needed to be installed in the same way, but in a different place. One of the first concerns with the implementation of all this hardware was the effect that it would have visually on the continuity and flow of the carefully designed curves of the metal structure. Great effort had also gone into designing a lattice type of construction in the frame so that the transparency and delicate sense of filigree would be expressed. Adding a lot extra hardware and equipment would certainly compromise the perception of these qualities.

The main strategy that we developed for dealing with the installation of the modules was to embed the modules within the interior of the circular arc elements. This would allow the outer curves of the metal structure to remain visually uninterrupted (see Figure 3.31). It was also determined that the best strategy would be to install the modules exclusively on the wing sections. The particular section of the upper circular arc element of each wing was modified slightly to help visually enclose the modules, or at least allow them to integrate more aesthetically with the curved frame. As the wing sections developed and became the elements which would accommodate the sound production system, the structural reinforcement expanded at the connection points of the two primary arc elements that form the wing. Since the serious tensile forces would now be primarily in the wing sections, it was important that they would have the structural integrity to handle the collective load of such forces.



Chapter 4 Process of Execution



4.1 A Digital Archetype as a Construction Paradigm

The word “Archetype” is defined in the American Heritage Dictionary as:

> An original pattern or model from which all things of the same kind are copied or on which they are based; a model or first form; prototype.

The secondary definitions of most dictionaries usually refer to the familiar Jungian sense of the word which is a collectively inherited unconscious idea, pattern of thought, or image universally present in individual psyches. In referring to the idea of a “digital archetype,” the first definition is intended. In the last decade or so, there has been a revolution in the Architecture, Engineering, and Construction (AEC) industry with respect to how buildings, monuments, large scale art installations, and other built projects get specified for construction. The AEC industry has essentially taken computational methods from the automotive and aerospace industries and has applied them to its own methods of construction specification. For the most part, that methodology utilizes a 3D digital archetype which is developed, literally built, within CAD space. Then the model is used to specify all of the parameters of construction, either directly to CNC fabrication machines or to human construction crews who will manually execute construction from the digital specification. Thus, the digital archetype construction paradigm is rapidly taking over the more antiquated construction processes which were driven by large sets of 2 dimensional paper drawings. Branko Kolarevic, associate professor and director of the Digital Design Research Laboratory in the Department of Architecture at the University of Pennsylvania, urges designers and artists to overcome their ambivalence about technology. "Architects have a chance to regain ground they've lost to contractors and other parties," he said. "We can overthrow traditional construction techniques with profound consequences" [Snoonian 2002].

4.1.1 Some History of Construction Specification

Since the time when people first began to build structures for purposes beyond their personal requirements, there has been a need to accurately communicate the desires of the owners and designers to those doing the actual construction. Such communication has become increasingly complex as our society and technology have grown and expanded. Through ancient and medieval times, the art of construction communications evolved gradually to include drawings supplemented by written words. This documentation was further supplemented by the direct supervision of master builders. By the seventeenth century, a contractual element was added in the form of written contracts between kings and their builders, thus establishing all of the fundamental elements of construction communications that are used even to this day: agreement, conditions of the contract, and drawings and specifications. By the beginning of the twentieth century, the building process, though still relatively simple and involving only a few participants by today's standards, began to require extensive written descriptions to supplement the construction drawings. This could be considered the beginning of the profession of construction specification writing as we know it today. Unfortunately, the number of documents that are now required, and the careful, arduous detailing of such documents for just about any large scale and/or complex construction project has become something of a liability as well as a formidable hindrance to the successful execution of such a project [Lindsey 2001].

With the advent of the 3D CAD medium, many architects and others in the AEC industry as well as some artists and sculptors immediately started to see the potential for greatly simplifying the process of specifying their designs to those executing the construction. As computer technology has advanced significantly in the areas of automation, robotics, fabrication, and prototyping, it has enabled the original designers to have an unprecedented level of control over the construction process and final outcome of the project. This is primarily because of the elimination of so much 2D paper interpretation of the design and an exceedingly direct connection between the original design information and the mechanisms which execute, or are responsible for, construction and fabrication.

4.1.2 Software and 3D CAD

In developing the design of the Chandelier, my goal was to satisfy the demands and constraints associated with engineering a new kind of musical instrument in tandem with trying to create a compelling work of sculpture which would express the important themes in the *Death and the Powers* opera. Several of those themes relate to complex and abstruse ideas about consciousness and existence. Therefore, it only seemed appropriate to pursue an abstruse form that might at the same time contain a dimension of beauty and austerity. It soon became obvious to me that the ideal medium in which to create such a piece would have to be 3D CAD, both for the reasons discussed in the beginning of this section and for what follows.

There is the question of why one should use 3D Computer Aided Design (CAD) techniques to approach the creation of sculptural art. I find that the answer is really twofold. First, the 3D CAD medium allows an artist or designer to invent formal ideas that would not be possible with other conventional media. This is exampled extensively by contemporary artists practicing today [Hart 2001] [Hild 2007] [Collins 1997]. Secondly, once such forms are created within the medium, they can easily be translated into physical, material reality through robust rapid prototyping or computer numerically controlled (CNC) milling and fabrication technologies. That is because the data of most 3D CAD models today has been greatly simplified with NURBS mathematics while at the same time it provides an exact definition of the model to be physically constructed. Previously, this model data consisted merely of an extremely large set of 3D coordinates which represented the vertices of a tessellated series of mesh surfaces. Such data would become incredibly cumbersome and elephantine with large models, and the worst part was that the accuracy of the geometric definition was a function of the scale of resolution of the tessellated facets in the surfaces. With increased resolution, there was higher accuracy, but at the expense of a bloated database. Buildings and other works of architecture and sculpture are now being constructed with a digital archetype driving the process. Architects and design professionals all over the world have been able to reclaim the “master builder” status of the Renaissance and control the construction process to a much greater extent than before. They are just beginning to fully assimilate the digital archetype paradigm in their practices.

There are a multitude of options for the available software that one can choose to work with in developing a project like the Chandelier. Many 3D CAD systems are targeted for specific industries such as aerospace, automotive design, jewelry, architecture, and so on. Most of them have specific feature sets that may cater to those industries or to those interested in particular tasks, like the modeling of complex surfaces for example. CATIA is one such system that still enjoys the singular distinction of having the most extensive and powerful surfacing tools of any other modeling system available. Maya and 3D Studio Max are used quite extensively for animation and visualization of characters and cinematic environments.

For the development of the Chandelier, it became clear that not only would the chosen 3D CAD system have to be capable of modeling complex ideas and offer the tools to do that, but just as important would be the ability of the system to define large complex models with simple and robust mathematical data that could seamlessly be used for the specification of rapid prototyping and fabrication processes as well as for the general dissemination of construction information. Rhinoceros ® is a system that was developed from an open source 3D library called OpenNURBS by McNeel which is an employee-owned company in Seattle, founded in 1980. This system contains many of the modeling features, including advanced surfacing, solids modeling, and extensive export options, that you can only find in very expensive top-of-the-line industrial strength systems like CATIA. The user interface has a very elegant design and is ideal for developing a project of the scale and complexity of the Chandelier.

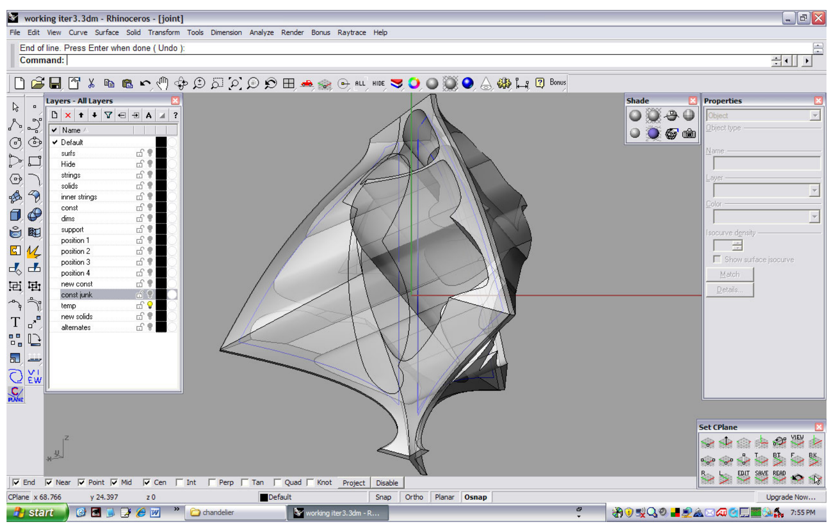


Figure 4.1 Rhinoceros ® 3D CAD modeling software, graphical user interface.

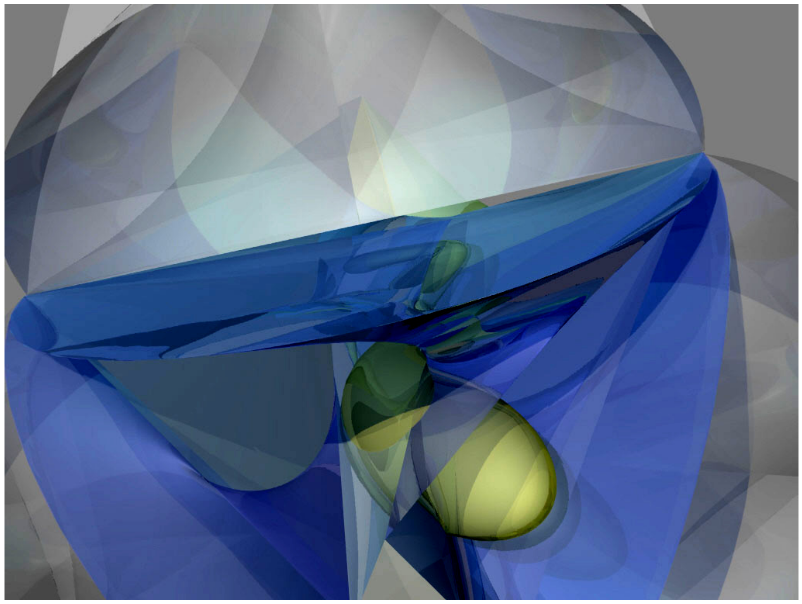


Figure 4.2 Digitally Rendered concept image of the Chandelier.

4.2 The Chandelier as a Digitally Conceived Form

The fundamental objective in developing the design of the Chandelier eventually became the effort to realize an authentic, digitally conceived form which could not be obtained through conventional design media. In this sense, the problem that we could say was defined for the project was then to model a theatrically compelling musical instrument sculpture that would be abstruse in form, but nevertheless able to be defined for construction. This did not mean that the piece would have to be unnecessarily complex or recondite for its own sake. It was very important that it would have a strong aesthetic value and sense of beauty, even if austere. The choice of which media to work with in developing the design stood before us. The tradition of conventional modeling materials is strong and offers the intrinsic connection with the physical behavior of real material. With the dematerialized medium of 3D CAD, this connection is lost. However, the following discussion will attempt to articulate why the 3D CAD medium was an utterly appropriate means to realize the design.

4.2.1 Limitations of Conventional Design Media

In making a comparison between conventional design media like paper, cardboard, foamcore, clay, plaster, or other physical modeling substances and the 3D CAD medium, one must first consider the inextricable material advantages of the conventional modeling tools. There is no getting around the fact that actual material will behave...well, like material. Take cardboard as an example. This is a very popular modeling material for architects and designers, because it has a similar behavior to building materials on a much larger scale. It has a rigidity in one direction and is much weaker in the other. This is very close to the way many types of constructed building panel units behave. Also, it has an internal structure which makes it relatively strong while still being light in weight and able to occupy a certain volume of space which is again very close to the properties of larger building materials at a very different scale. As a result, the behavior of the modeling material itself becomes a primary advantage by informing the designer about real world material behavior as they work. Also, the physical behavior of these substances, when they are assembled to form various structural conditions, will inform the designer about all kinds of natural consequences that relate to structure and the static forces which are inherent aspects of any construction of parts, regardless of scale.

However, this natural material behavior of conventional modeling substances is also their greatest disadvantage. What these modeling materials are actually capable of is limited by this very behavior. To be sure, material behavior is extremely limiting if one is interested in modeling shapes that are conceptually difficult or that follow an alternative logic like a mathematical model for example, or really any model that is anything other than that which conforms to material behavior. Clay will always behave like clay. It will only ever do what clay does. For example, if one wants to model a very flat glass-smooth planer shape with clay, it would be next to impossible. If one wants to use a piece of glass for such a shape, but then wants to deform it somewhere on the surface of the plane in a freeform, yet controlled swell, that would be almost impossible as well, because glass simply won't do that. It would be trying to force a material to defy its own behavior in that part of the model. This natural limitation is profound with respect to what the human imagination is capable of conceiving. As I will discuss shortly, it is actually that which may not even be imaginable that the medium of 3D CAD becomes an extremely powerful means to attain.

4.2.2 3D Digital Modeling Transformations

There is always a very extensive set of 3D modeling tools available in any serious 3D CAD system. Rhino is no exception. The typical configuration of functions will usually break down into the following basic categories:

1) Basic wireframe elements
2) Primitive shapes
3) Basic surfaces and solids
4) Advanced and freeform surfaces and solids
5) Operations and transformations

The first class of functions are the basic wireframe elements and refer to all of the tools that produce the fundamental geometric objects like points, lines, planes, canonical curves (circles, ellipses, parabolas, etc.), and freeform curves. These elements are the fundamental building blocks of the more complex higher level elements like surfaces, solids, and volumes. The second class of functions essentially generate basic canonical shapes like spheres, cubes, cylinders, pyramids, and so on. They can either be defined as solid volumes or enclosed surfaces. These become the building blocks for developing more complex models using the sophisticated operations and transformations given in the fifth class. The third class of functions start to get into the creation of solids and surfaces that are more complex than the primitives. They generally include algorithms for extruding or sweeping some kind of template which would be defined by a wireframe element. This would be like a cookie cutter action in which the template extrudes a solid or surface shape by either a translation or rotation of the 2D template shape. This class would also include basic planer faces or surfaces. The fourth class of functions offer a completely different set of methods for producing solid and surface objects. These methods generally involve the formation of net-like structures which are made up of fully flexible 3D space curves that run in two perpendicularly related directions. There are other sophisticated functions in this class which generate solid and surface objects through the interpolation between a series of 3D space curves. This method is often called "lofting" which is a term taken from the craft of ship building. In general, this class of functions deals with the construction of complex surfaces and solids that vary freely through 3D space.

The fifth and last class of functions deal completely with the modification and manipulation of objects rather their creation. When it comes to modeling sculptural or artistic ideas in general, these functions are in many ways the most exciting, because they will often lead to unpredictable, astounding, and unimaginable results. With this class, one can do the most fundamental moves like basic translations and rotations of objects in space. However, there are other functions which allow the manipulation of objects through a wide range of available mathematical operations as well as scaled distortion transformations and affinities. Affinities, in the lexicon of 3D modeling, are global, scaled expansions or contractions in the proportions of objects which can be active along one, two, or three dimensions. These scaled, proportional changes can also be imposed at an oblique angle to the coordinate axis of the objects, which can really distort them in an extremely interesting way. There are what might be considered a subclass of functions that relate to Boolean mathematics. They involve the operations upon surface and solid objects which correspond to Boolean mathematical functions such as union, intersection, and difference. For example, two solid objects which share the occupation of a common space domain can be the input to a Boolean operation. The output object will be the result of the specific union, intersection, or difference function. It is through these kinds of transformations that a sculptor may experiment and develop exceedingly compelling formal ideas which would not have been attainable through physical material modeling.

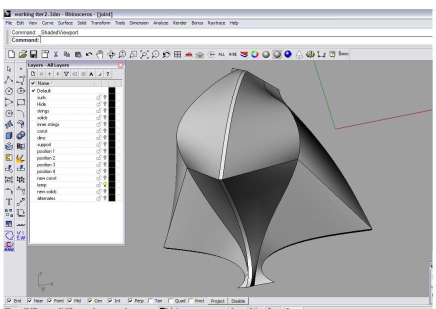


Figure 4.3 3D solid volume of the interior space envelope of the Chandelier.

These five general classes of functions constitute the general current paradigm that most of the available 3D CAD software systems (commercial or academic) seem to follow. It is interesting that this paradigm has not changed much since the inception of 3D CAD over three decades ago. We are relatively stuck in this way of thinking about 3D modeling. Nevertheless, this paradigm has worked very well for most applications and allows for a great deal of flexibility in what is possible to create.

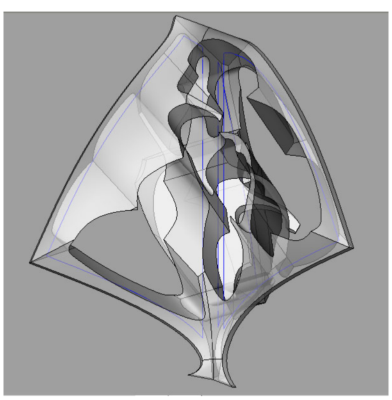


Figure 4.4 3D interior volume after a series of Boolean operations.

4.2.3 Conceiving the Inconceivable

The Chandelier design was initially conceived with very loose sketches on paper. McDowell began to sketch a few principle ideas in such a manner that expressed some general concepts which connected with the *Death and the Powers* opera and the work of other relevant artists such as Naum Gabo. From his sketches and much of the same material, I began to draw my own sketches on paper in order to work out some initial ideas which would formulate the premise of the design. At that stage, I purposely avoided any commitment to concrete formal

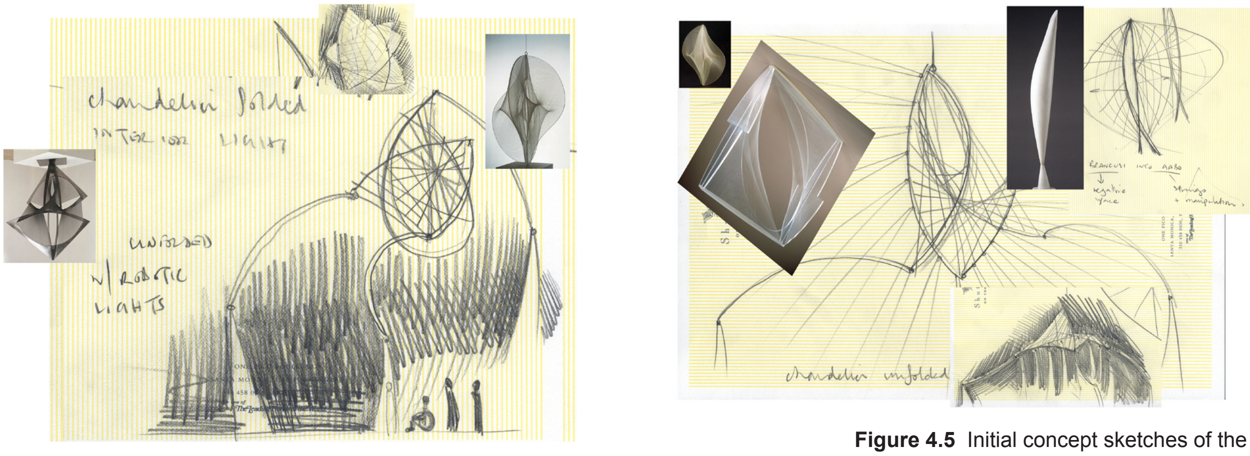


Figure 4.5 Initial concept sketches of the Chandelier by Alex McDowell.

ideas, because it soon became clear that the most appropriate medium for realizing the basic form of the Chandelier would be the 3D CAD environment. As previously stated, this design environment was chosen primarily out of the interest to conceive a form that would not ordinarily be conceivable with conventional physical modeling material. This notion has a strong alignment with an "inconceivable" form of consciousness to which Simon Powers will transmute in the opera. However, the inevitable requirement for the piece is that it must be constructible within reasonable means.

The design is framed with several trussed, circular and parabolic arcs which form a general triangular structure. This network of arcs forms a frame that holds a very organic, almost nebulous looking centerpiece. The centerpiece is in many ways the heart of the design. However, it is certainly not intended to be viewed or understood as separate from the rest of the Chandelier. But given the strong, canonic geometries which surround the center, it naturally becomes the visual core of the entire entity. It is the juxtaposition of this organic, somewhat amorphous centerpiece element with the highly symmetrical, canonic geometry of the surrounding structural frame that perhaps best states the fundamental idea, the parti if you will, of the Chandelier design. The intention was to express something about the organic nature and evolution of consciousness which exists in the physical universe of

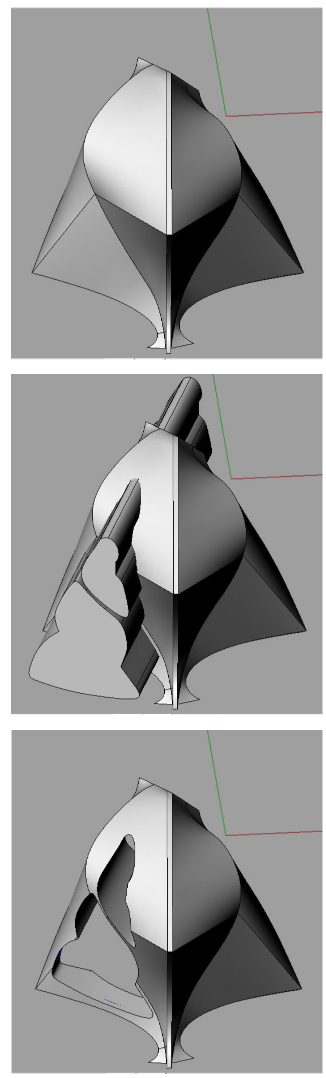


Figure 4.6 Sequence showing a Boolean subtraction of the interior volume.

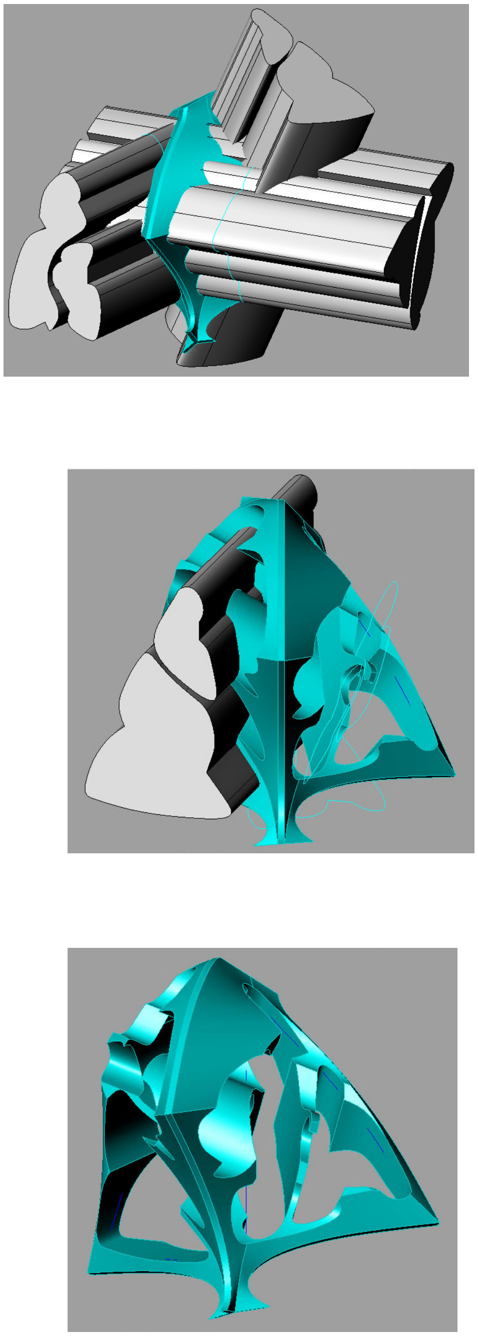


Figure 4.7 Illustration of the relationships of the geometric solids used in the Boolean operations of the interior volume.

mathematical laws and geometry.

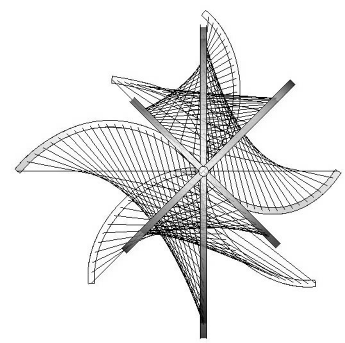
In the attempt to develop a design that would constitute an authentic, digitally conceived form which would be both aesthetically powerful and conceptually abstruse, I began to make a study of various twisted surfaces that would represent the intertwining implicit surfaces of the string arrays. This kind of implicit surface is of a certain type called a "ruled" surface [Watt 1999]. A ruled surface can be twisted, but can only be curved in one direction; the other direction is always lines or "rules." Since the strings, which are under a great deal of tension, are geometrically analogous to a progression of ruling lines, using this kind of surface to model the strings proved to be very accurate. Eventually, after a series of iterations with several of these intersecting surfaces, a meaningful and useful form began to burgeon. Around the same time, it became useful to experiment with progressive sequences of Boolean operations on the central volume which started to appear as the negative space within the overall form. This negative space in the center of the composition began to define an empty volume or envelope which, in itself, could be understood as a shape. And this shape was, in essence, being sculpted by the implicit string surfaces surrounding it. The idea of working with an interiorized space as a shapeable mass is an intimate notion for the architect. In a very literal way, I defined a solid mass which was perfectly described by this interior volume. This shape became a point of departure for a series of explorative transformations using mostly Boolean operations as a sculptural mechanism. What emerged was a form that was truly architectonic in character.

4.3 Progressive Versions and the Iterative Process

What follows is, more or less, a chronological progression of the primary iterations of the Chandelier model. Together, they constitute a study of variations on a few themes that get established early. What is most interesting in making a study of the progression is to note what formal ideas remain present through all of the iterations and what ideas change entirely.

4.3.1 First Iteration

The first proposal for the Chandelier design that was fully modeled in the 3D CAD environment came to fruition mostly through a translation of some initial paper sketches which themselves were interpretations of McDowell's sketches. Though it was not a particularly conscious move, there is the almost unmistakable form of a harp which is repeated, twisted, and rotated. The implicit string surfaces, even at this stage, begin to define a central shape through the void negative space which takes a form that is reminiscent of a Brancusi-esque bird.



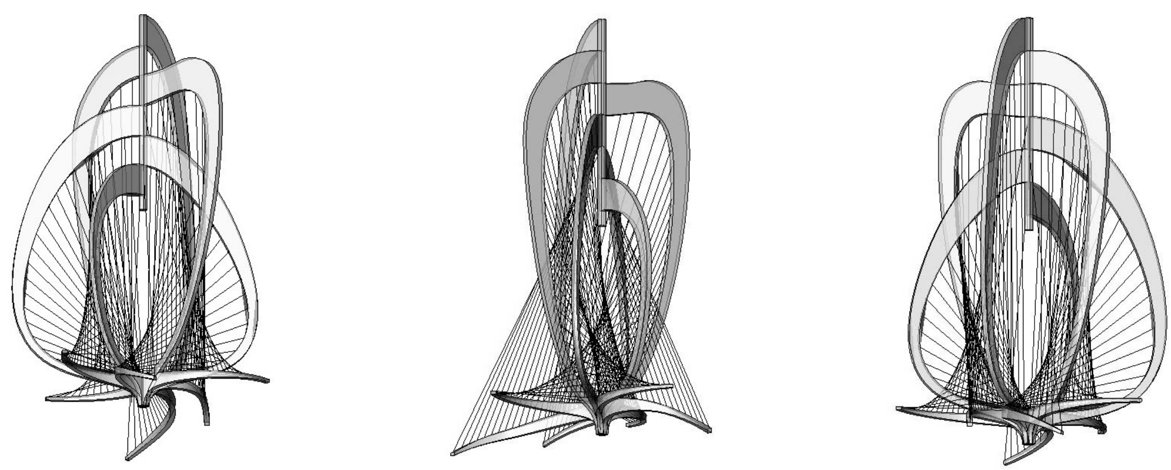


Figure 4.8 Digital images of the first iterative version of the Chandelier.

4.3.2 Second Iteration

In the second general iteration, there is a pretty radical shift away from the "harp" form and to a more ethereal, softer treatment of the string surfaces. There is also the appearance of a highly geometric theme which encompasses a symmetrical composition of canonical curves. These curves include circular

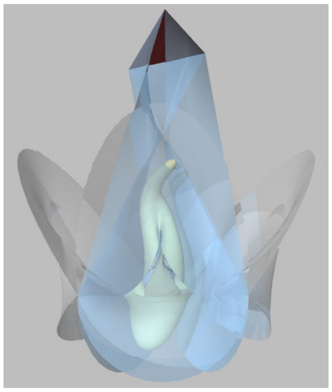


Figure 4.9 The appearance of the worm-like shape in the digital concept model.

and parabolic arcs that visually circumscribe the form of an egg. It could be said that the loosely implied egg shape alludes to Simon Power's birth or rebirth, however it wasn't a literal intention, though perhaps it took this form on a somewhat subconscious level. The theme of a strong, pronounced geometry also gets manifest here, for the first time, through a triangular symmetry which embodies a tetrahedral form within the interior space. This was more consciously introduced with the geometrical significance of the Platonic tetrahedron in mind. It is this one, of the five Platonic bodies, which has

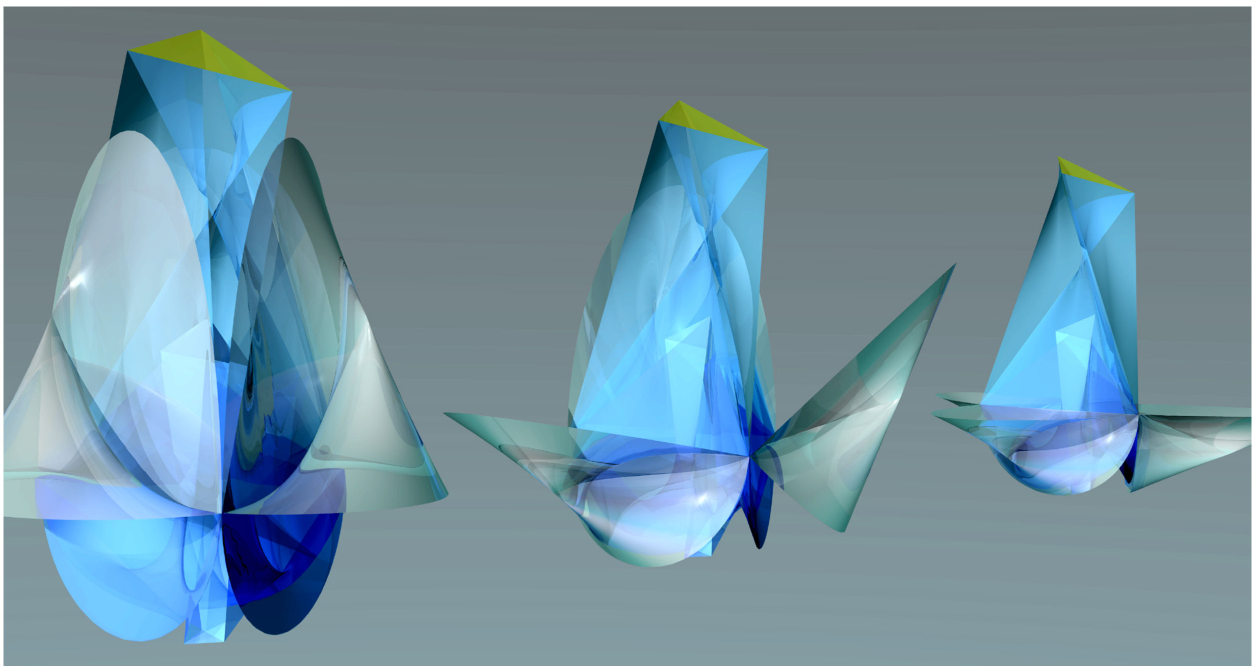


Figure 4.10 The implicit tetrahedrons appear in the 2nd version concept model.

been considered by many geometers, mathematicians, and Pythagoreans, through the centuries, to be the simplest and strongest enclosed shape to exist in the known universe [James 1993].

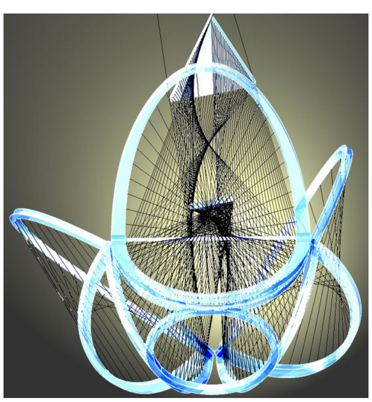


Figure 4.11 Articulation of the string surfaces and support frame.

Perhaps, the most whimsical and ultimately inconsequential element that appears during this iterative phase of the design is the worm-like shape, placed in the very center (see figure 4.9). This was intended to breath like an inflating balloon, and was initially meant to incite a kind of horror effect which might indicate a Frankenstein-like result in Simon Powers'

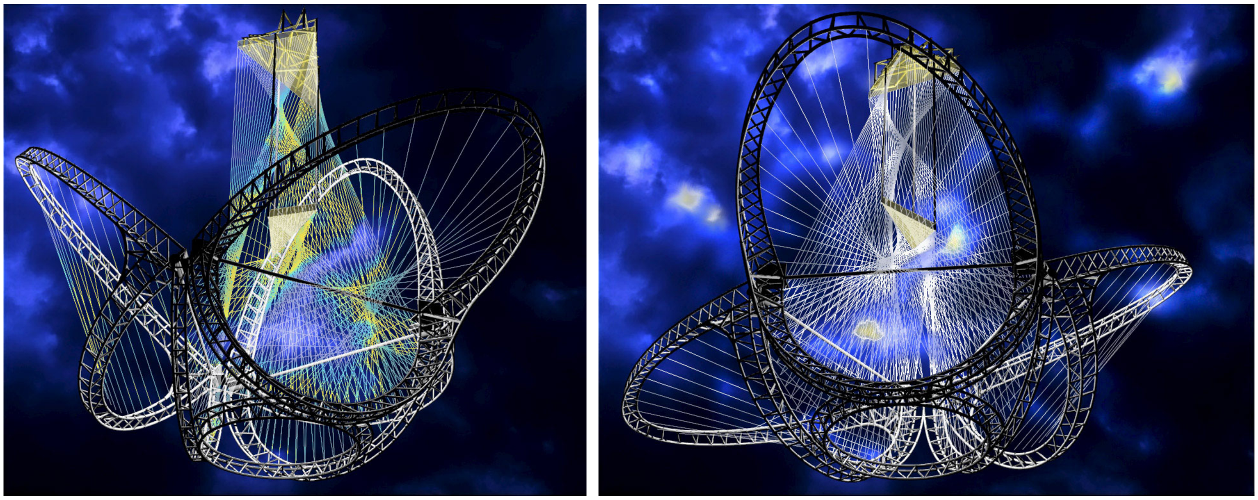
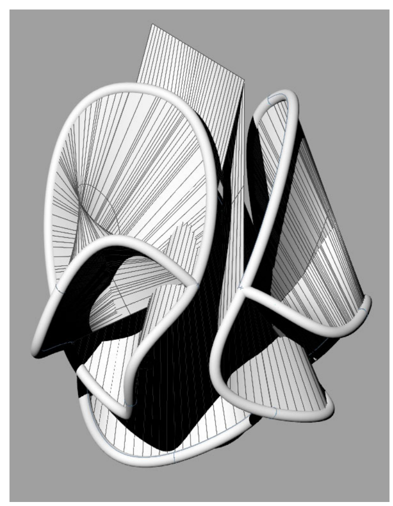


Figure 4.12 Digital rendering of the full articulation of the frame and strings.

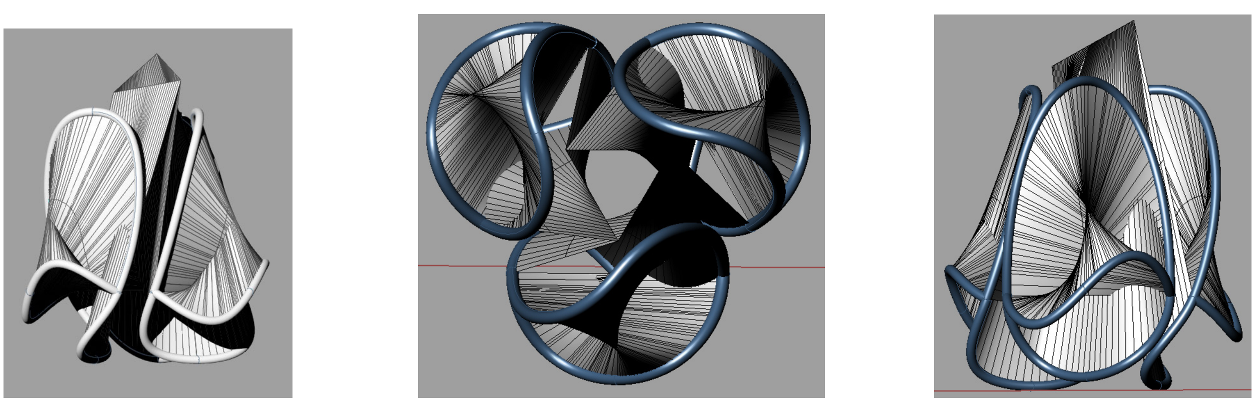
transduction into the System. As McDowell did not respond favorably to the shape, it eventually became relegated to the status of a placeholder to be worked out at a later time. It was a good thing, and showed a sapient vision on the part of McDowell.

Figure 4.13 Digital renderings of the 3rd version concept of the Chandelier.



4.3.3 Third Iteration

The third iteration shows an increasing complexity with the basic design of the former iteration. Essentially, the entire metal frame structure gets twisted so that all of the formerly planer arc elements become curved in three dimensions. The main consequence of this is that the form becomes such that there is no angle from which the piece can be viewed that would have a straight line or planar look to any part of it. In other words,



every structural piece always has two dimensions of curvature. However, there is still a rational component to the curves that is revealed only through certain discrete views of the piece. If it is viewed from one of these particular angels, which is defined by the absolute perpendicular line of sight to one of three wing sections, the freeform looking curved geometry will suddenly lock into a very rational, canonical formulation of arcs which outline the egg shape. This is another great example of a way of modeling which is unique to the 3D CAD medium. The artist can work with multiple two dimensional designs or views that are projected to intersect at different three dimensional angles to create a uniquely inconceivable 3D spatial entity. This could be generated through a Boolean intersection of the projected views.

This iteration was ultimately not pursued because of the associated expense connected with the construction of the greatly increased number of curved metal pieces.

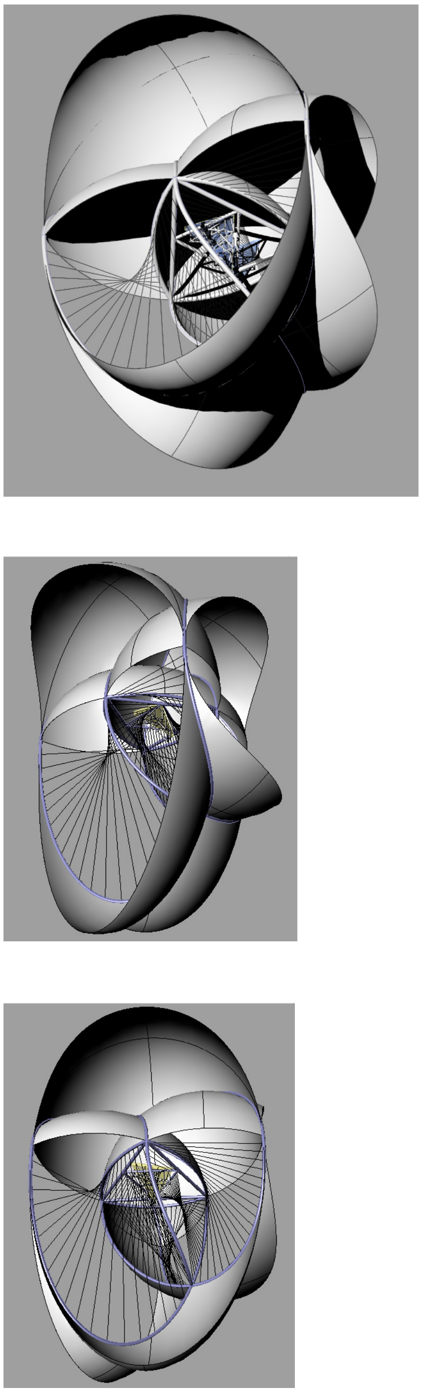


Figure 4.14 Digital renderings of the 4th version concept of the Chandelier.

4.3.4 Fourth Iteration

The fourth iteration of the design represents the greatest departure from anything that had come before and moves onto a completely new path. It was an attempt to try to shake up our current thinking about the Chandelier design. If for no other reason, this sort of departure can serve to help the design team question some of the accepted maxims that have driven the development of the current design, and which have possibly been under-considered and established in haste. In this iteration, I began to think more about the interaction of light and surfaces. Given that there were fairly stringent mechanical constraints on the actual movement of the piece, I began to focus more on the power of theatrical illumination combined with interesting textural surface form as a means to achieving movement and, ultimately, the effect of metamorphosis. Here, the tetrahedral idea is retained, and the egg form receives a more literal treatment. The design is attained through a series of Boolean intersection and difference operations involving three different shapes and sizes of intersected spheres and egg shapes. About the only part of this exploration that gets forwarded to the final design is the qualitative knowledge of the effects of light interacting with surfaces which can be exploited to give movement to shapes. The design, as a whole, was not pursued further.

4.3.5 Final Version

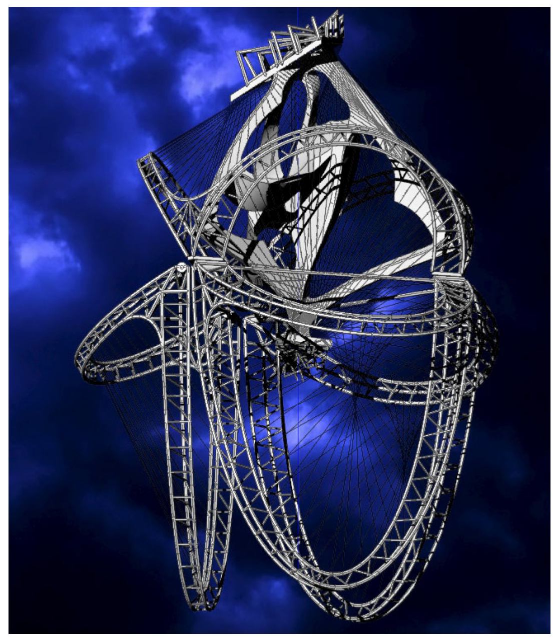


Figure 4.15 Digital rendering of the final version with full articulation of the support frame and strings.

The fifth and final iteration of the Chandelier design makes a return to a form that is most closely associated with the second version. However, it is a testament to the iterative process that each exploration contributed something important to help inform the final design. On the most basic level, the piece gets turned upside down with respect to the second iteration. This was a result of the narrative demand that the wings needed to embrace, envelop, and lift human characters in the opera. It forced a primary change with what was going on with the string surfaces in the center. Also, the volume envelope in the center becomes more interesting and complex as a result of changes in how the string surfaces enclose the interior. This became the final incentive for the development of the central form which, in my opinion, fully completes the design.

In developing the central form, I converted the interior space envelope into a solid mass, and then went forward with a series of explorative operations on the mass as a study of relationships between interior and exterior, surface and light, mass and space, transparency and structure. It was important that the central form would have the qualitative surface

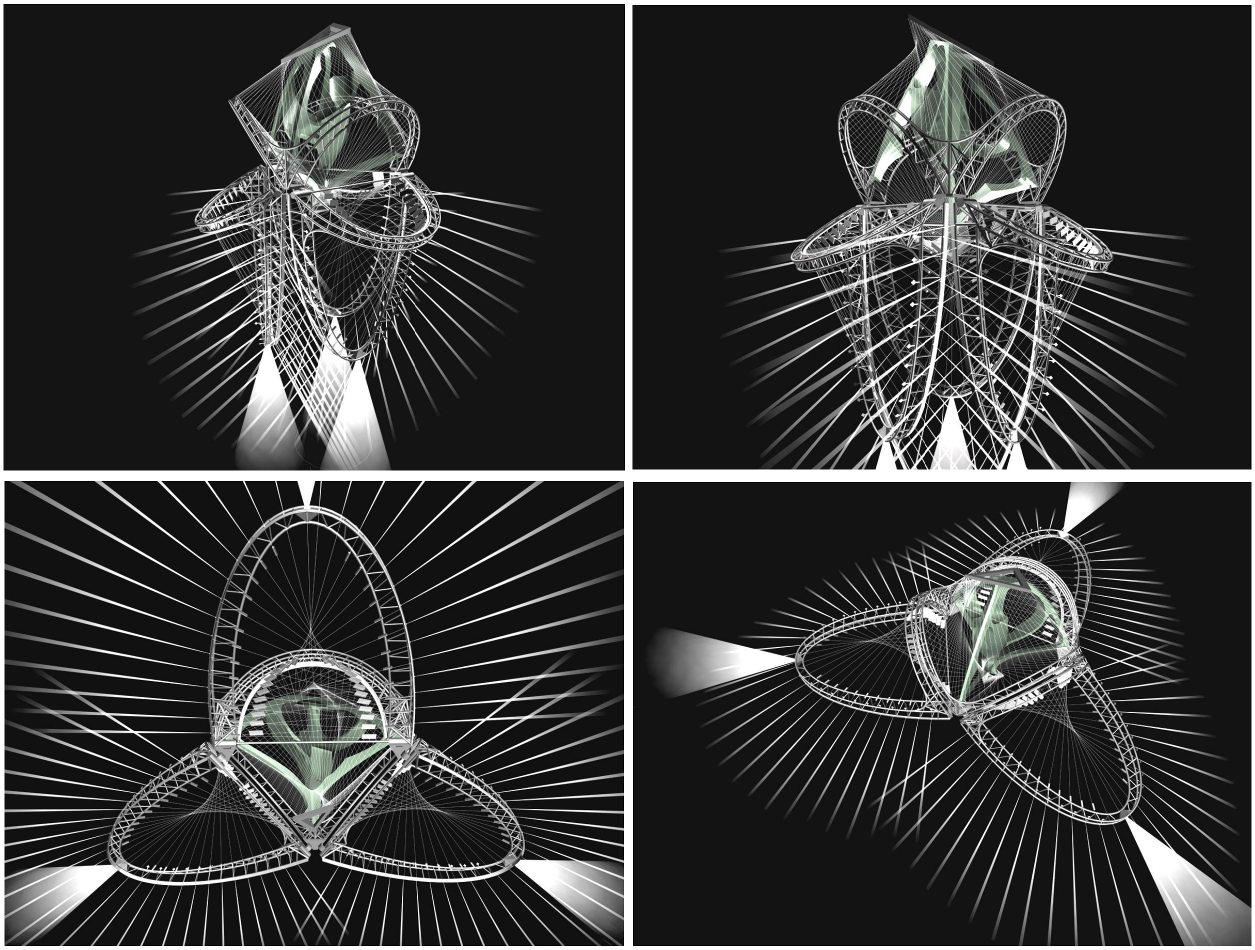


Figure 4.16 Digital renderings of the final Chandelier design with illumination scheme (Imaging by Arjuna Imel).

characteristics which would allow the intense illumination of theatrical spot-lights to visually vary the perceived shape through shadow and contour. Yet, it should not have so much surface area that it would diminish the transparency of the piece overall. This was a careful balance.

4.4 Movement and Metamorphosis Through Light

One of the most important visual objectives of the Chandelier project was to achieve a strong sense of movement. As discussed in section 3.4.3, the mechanical constraints established through an initial analysis seemed to indicate that movement beyond the independent rotational action of the wing sections would be exceedingly difficult to engineer, on top of which, there were considerable safety issues that had to be observed. Therefore, the thinking about movement turned more to the theatrical and musical context of the opera. It has always been the case in architecture and in the theater that light and shadow, surface and texture are the elements that convey form. If these elements can be made to operate dynamically, then the possibility of a dynamic form arises.

A number of illumination studies were conducted by modeling the emulations of the Chandelier under specific lighting conditions within the 3D CAD environment. As the three wing sections are capable of moving independently through a ninety degree rotational range, the possibilities for the dynamic illumination of the piece are practically infinite and very exciting. Here, I propose a scheme in which a set of intense spot-lights are mounted at the tip of each wing section, but are turned back to point at the central form. This could be in addition to any number of other mounted lighting schemes which appear in other rendered images contained in this thesis document. Three sequences of images are presented here. It is important to note that in all of the images in all three sequences the view and orientation of the Chandelier piece does not change. It then becomes only a sequential study of the movement that the spot-lights impart on the central form. Ideally, the best way to view this study would be in the form of an animation, because the sense of movement and metamorphosis of shape would be explicit. The still images give slices of what would be in a continuous form.

The first sequence is the simplest depiction of the three sequences. It shows the effect of one spot light mounted on the tip of a wing section that will rotate through its entire ninety degree range. With this very basic action, the visual movement that happens throughout the center is interesting nevertheless. The second sequence shows two wing sections simultaneously moving through their range in opposite directions. The intensity of illumination in each spot light remains constant

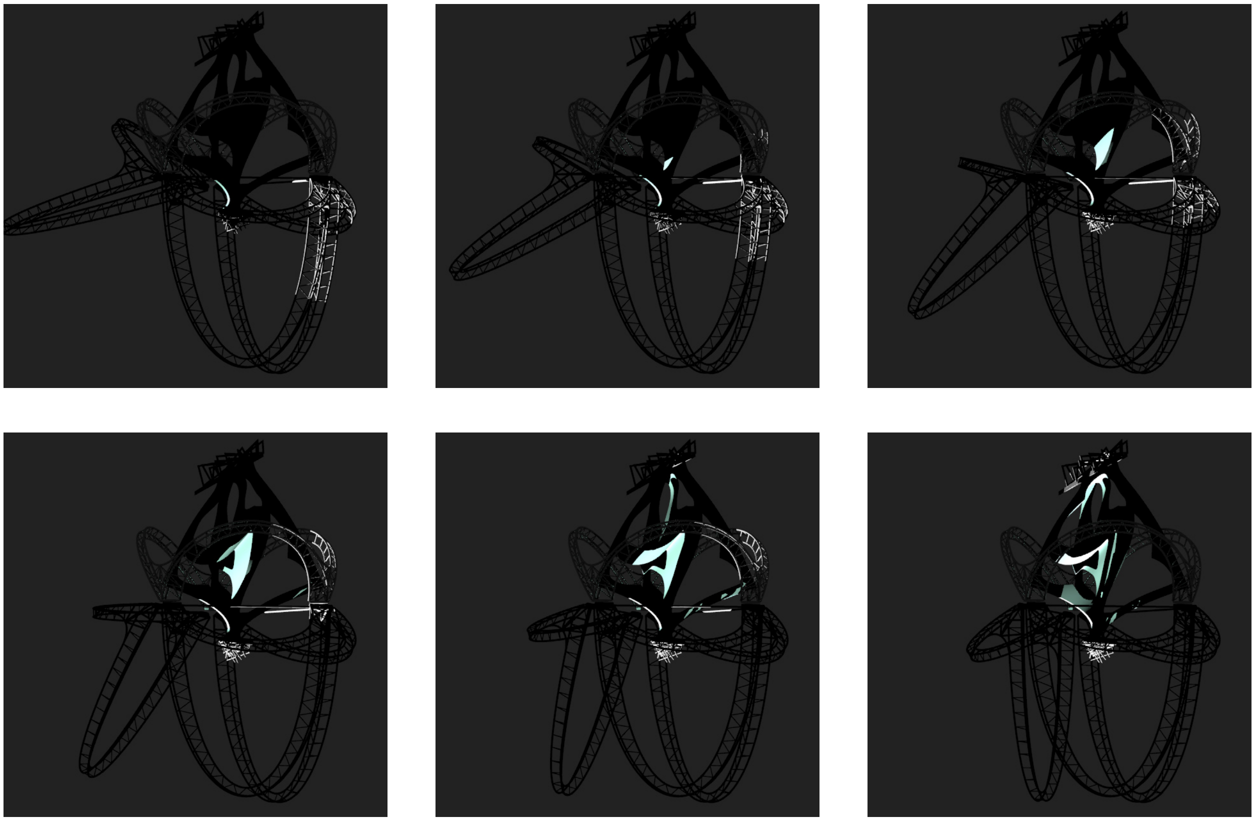
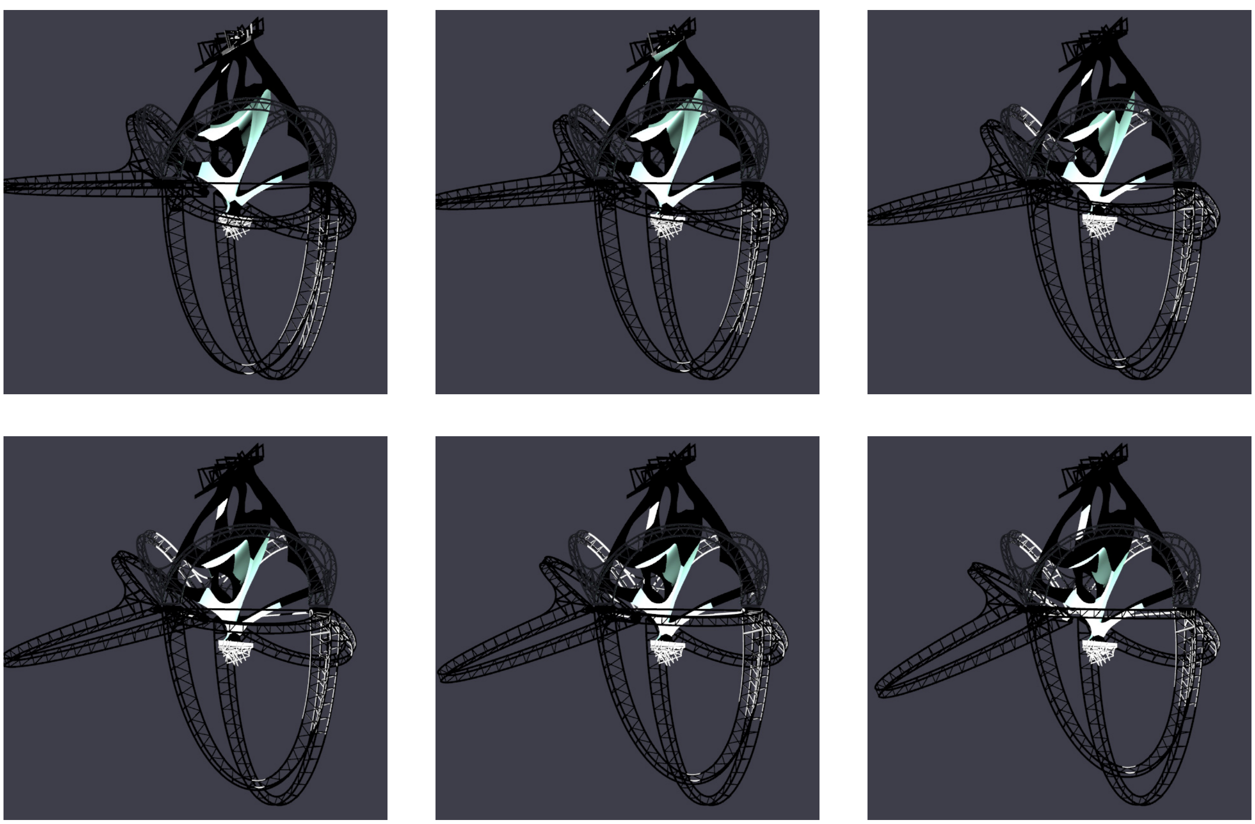


Figure 4.17 Central form lighting sequence of one wing rotating through the full 90-degree range. (Above)

Figure 4.18 Central form lighting sequence of two wings rotating in opposite directions. (Below)



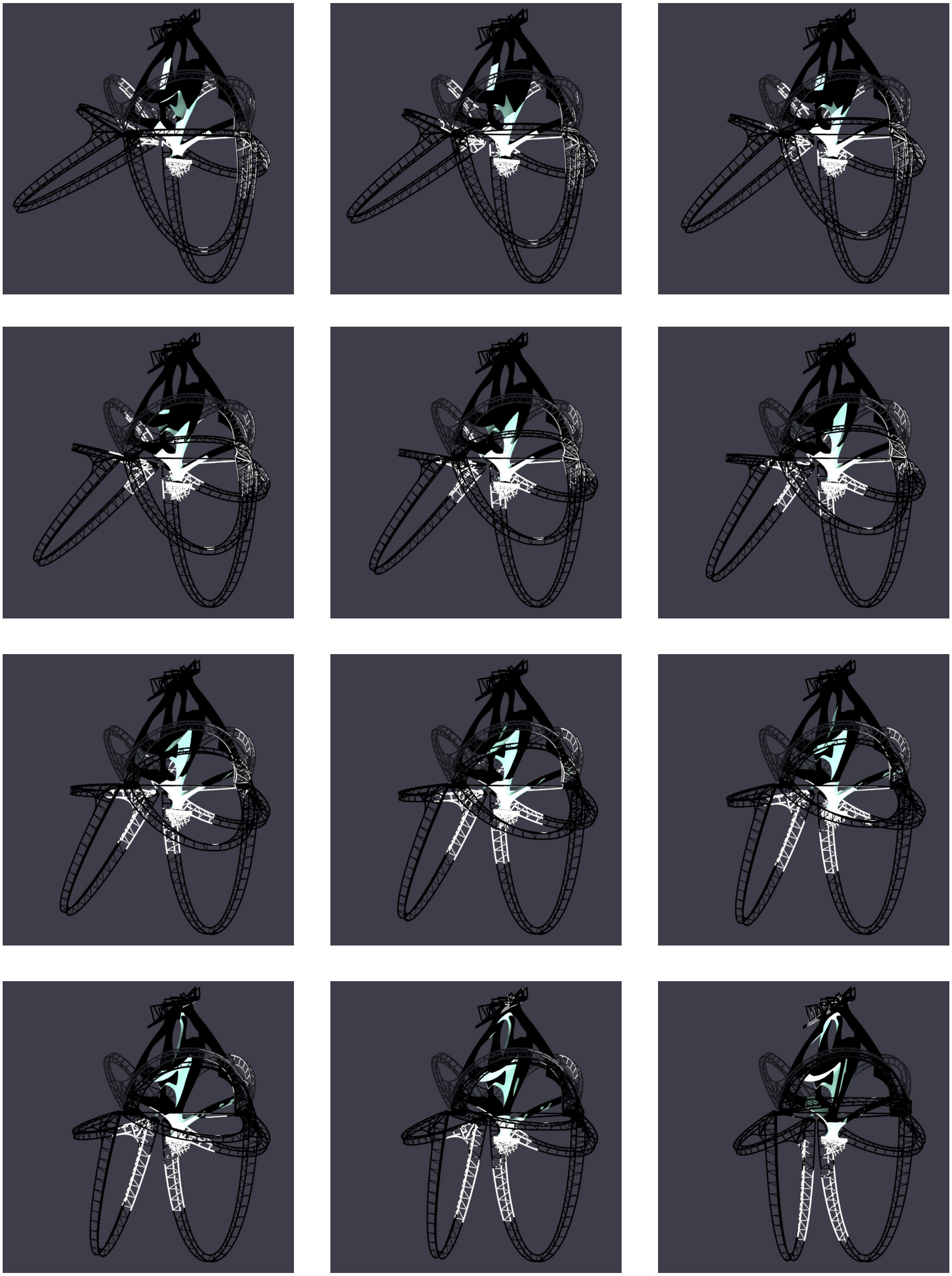
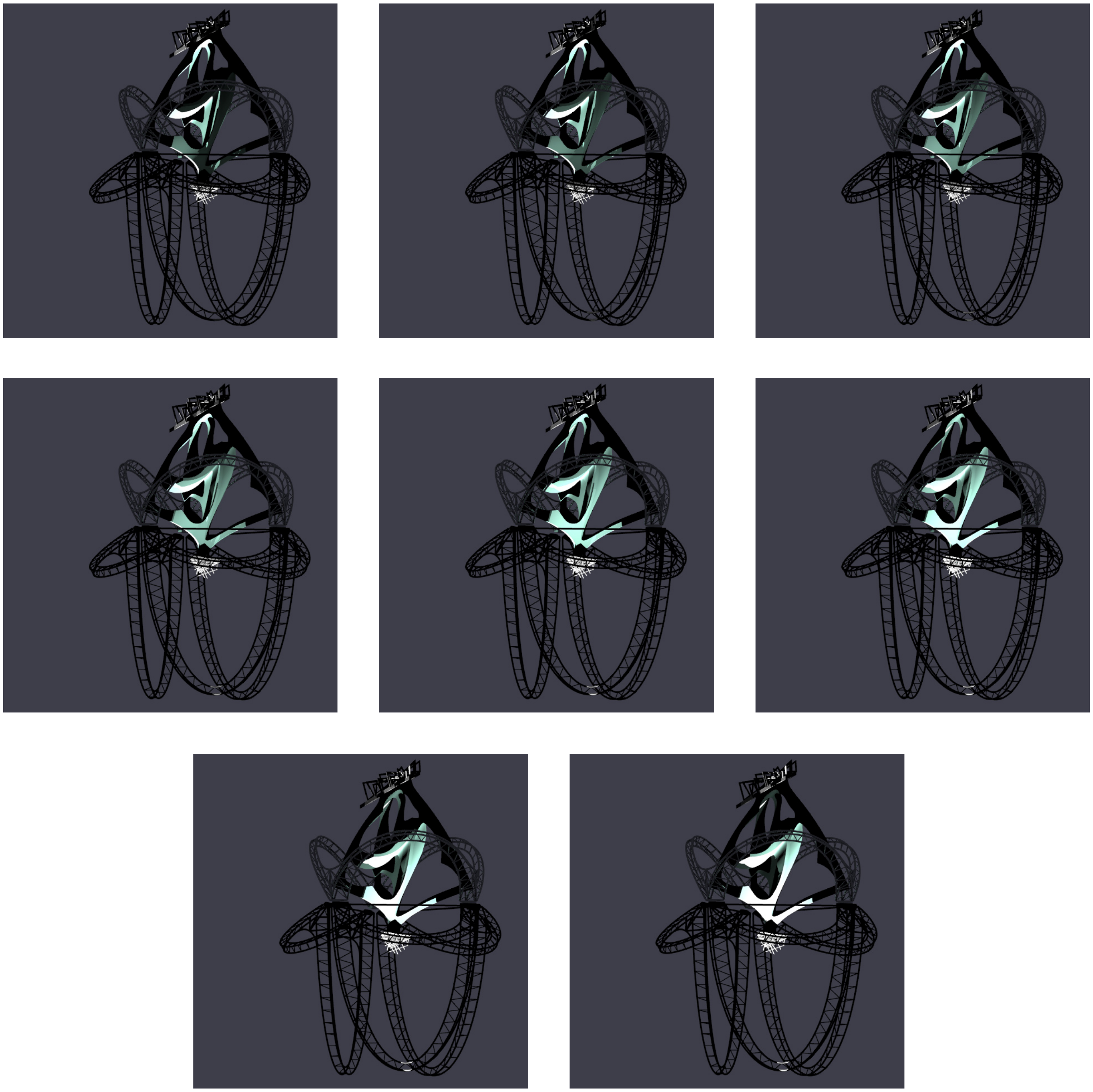


Figure 4.19 Central form lighting sequence of two wing section spot-lights changing intensity.



in the first two sequences. In the third sequence, there is no movement from the wing sections. It shows only a progression of changing intensities of two spot-lights mounted on their respective wing sections. It should be clear that even the mere changing of intensities of the spot-lights will achieve the visual sense of movement and shape change of the central form.

4.5 From Digital Archetype to Physical Prototype: The Model

As the completion of the Chandelier design came to a close, the 3D CAD digital archetype of the piece was ready to be exported for prototyping and construction. However, it is the common practice of architects and designers to build a verification model at a sizable scale in order to demonstrate the constructibility of the design. Given the dematerialized nature of the CAD model, taking the trouble to construct a physical verification model will often uncover certain issues and problems related to material, structural, and functional conditions. For the purposes of the Chandelier, this model was supposed to be, in many ways, the proof of concept, the definitive demonstration that not only could it actually be constructed, but that it would also function successfully as a kinetic sculptural structure and as a compelling performance object in the context of the opera.

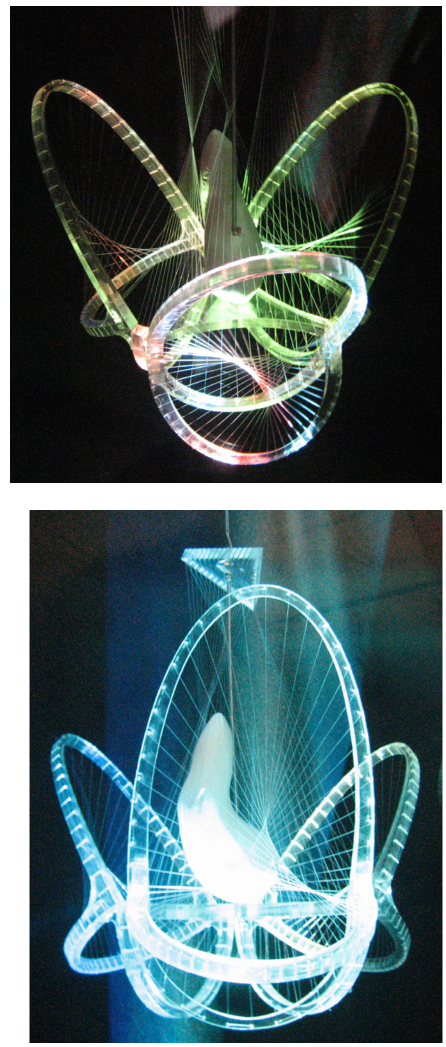


Figure 4.20 Early version of a physical prototype of the Chandelier constructed from laser-cut acrylic and plastic line. Digital templates, extracted from the Rhino 3D master model, were used by the laser cutter to precisely fabricate the curved pieces with exact spacing of the notches which hold the strings in position. Such precision is very difficult without a digital archetype.

4.5.1 Rapid Prototyping

One of the important tools used in the 3D CAD and manufacturing (CAM) process is rapid prototyping. This allows the instant physical verification of just about any 3D CAD model. There can be a large increase in efficiency and economic incentive to use such a verification stage in order to preemptively catch any possible problems with structure or interference in the design. It also helps enormously to be able to actually see, touch, and study a physical archetype of a model that has been living in 3D CAD space. When it came to building the physical prototype of the Chandelier, the small rapid prototype model became a vital tool for the accurate construction of the entire assembly. Having the ability to examine and reference a complete 3D physical archetype more fully informed us about the geometry of construction and allowed us to constantly verify the progress of constructing the physical prototype.

Figure 4.21 InVision stereolithography rapid prototype machine by 3D Systems Corporation.

There are many different types of rapid prototyping machines on the market. The Media Lab offers access to a few different machines. Because of the fine detail of the metal construction in the Chandelier, it seemed that the most appropriate machine to use was the stereolithography InVision machine by 3D Systems Corporation. This machine uses a process that slowly builds up a 3D structure by laying down very thin consecutive sheets of acrylic photopolymer material which is sensitive to ultraviolet laser light. The laser has the effect of curing or hardening the material layer by layer until a complete 3D shape is developed. As each layer builds up, it fuses to the cooling plastic of the previous layer, forming a sturdy object. This technology requires the buildup of support braces, which can be made out of either the same plastic and broken off, or a soluble material that can be dissolved in a soap-and-water bath. Each printer of this type features a different support option. But the new software systems build in the supports, so those don't have to be included in the original drawing. This technology was primarily developed for industrial and mechanical industries

Figure 4.22 Rapid prototype model of the Chandelier wing section being manually excavated and cleaned.

to prototype machine parts, but there has been a kind of renaissance, and people are beginning to use it for architectural and fine arts modeling as well.

Notice the rapid prototype model of one of the wing sections of the Chandelier. The real benefit of this particular machine is the fact that the photopolymer material is quite strong and durable enough to hold together at such a small scale wherein some of the component pieces of the wing section are only about a millimeter in thickness. This small but detailed rapid prototype model helped guide several construction details of the 1/4 size physical model.

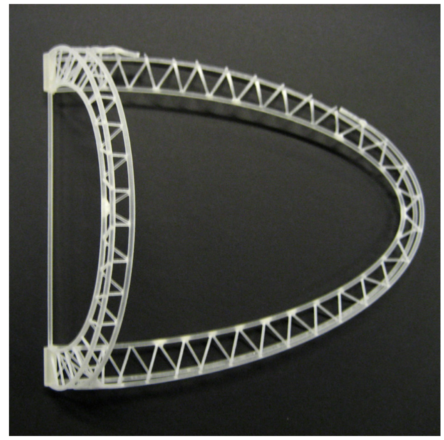


Figure 4.23 Excavated rapid prototype of the wing section.

4.5.2 Materials for the Model

We considered a wide variety of different materials for the construction of the physical model. As we had decided that the model was going to be exactly a quarter of the size of the actual built Chandelier, and at that scale, the constituent arc elements of the frame would end up being quite narrow in some places, it became a reasonable strategy to construct the model out of metal so that it would have an adequate strength to support the tension of all of the string layers. It would also have to endure the stresses of being hung without any noticeable deformation in the structure. So, the question became what type of metal would be appropriate. It had been previously determined that the actual Chandelier frame would be constructed out of aluminum for its combined properties of strength versus weight. Practically any other metal would simply be too heavy to be feasible in such a large structure. However, for purposes of the physical prototype, aluminum would be far too tedious to work with as a modeling metal. Eventually, we realized that the metal which offered the best all around combination of cost, aesthetics, strength, and workability was brass. The fact that brass could be welded, or more accurately soldered, was a huge plus in light of the fact that there were going to be over 600 welded connections in the final model.

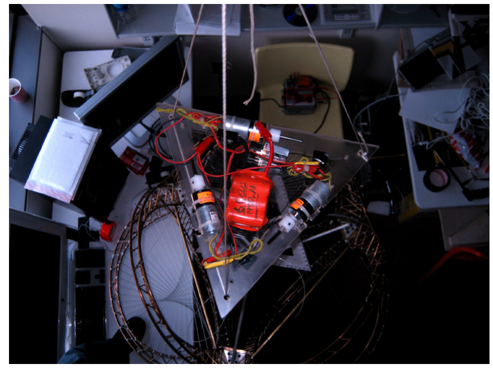
For the center form of the Chandelier model, it was determined that aluminum would be the best skeletal support material. This central skeleton would constitute the basic structure that would hold all of the major components of the piece together as well as provide the internal support for the metal surfaces of the central form. From a fabrication point of view, 1/4 inch aluminum sheet would be relatively easy to cut and weld. As far as what the best material for the strings would be in the context of the model, we decided to use a metallic wound string which could be tensioned easily and maintain the form of a very straight line without much actual tensile force. Real piano wire or other solid metal wire would have required too much tensile force to achieve a straight line without kinks. For the purposes of the model, it wasn't necessary to have the strings behave like musical strings since there was no practical way to emulate the physical sound production in any case.

Figure 4.24 The manual formation of the curved brass frame using a laser-cut plywood template.

4.5.3 Process and Execution

In order to begin the construction of the physical model which would be a 1/4 size prototype of the Chandelier, several templates of the exact geometry of the constituent parts would have to be extracted. These digital templates were used to laser cut exact forms out of plywood; and the plywood forms were then used as guides to bend and form pieces of brass tubing to the exact shape and size specifications of the design. Digital templates were also used to cut and fabricate the aluminum support components of the central form. The length of every single brass chord piece of the trussed arc elements was extracted from the digital model and exported into a listing that was used for the manual fabrication of the elements. We also made an analysis from which the angular measurements of every piece in the trussed components were exported. Only through the rigorous extraction of such detailed information was it possible to accurately “reconstruct” the physical replica of the digital archetype. This is particularly true when trying to construct a geometrically complex physical prototype from the digital archetype.

With the exact specification given by the digital archetype and the superb craftsmanship and help from Samuel Kronick, a UROP assistant, the accurate realization of the physical prototype was achieved. We were quite thrilled with the functional and formal qualities of the prototype, and it allowed us to continue work on engineering a preliminary motor drive system that would move each wing section independently. Most of the electronics and drive motors are installed on a triangular platform well above the main body of the Chandelier. As each wing section can rotate about a primary axle which connects to the main body, the rotational motion is directly controlled by a dedicated motor which takes up and releases a cable assembly that is attached to the upper part of each wing section. For purposes of demonstration, we configured a radio control system to communicate with the motor drives controlling the movement of the wings.



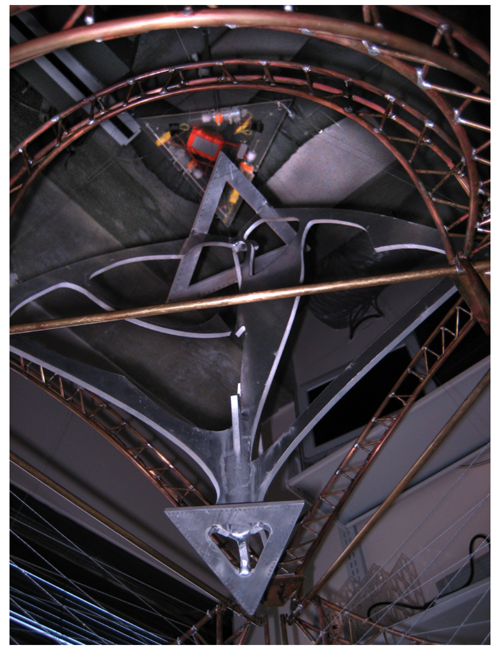
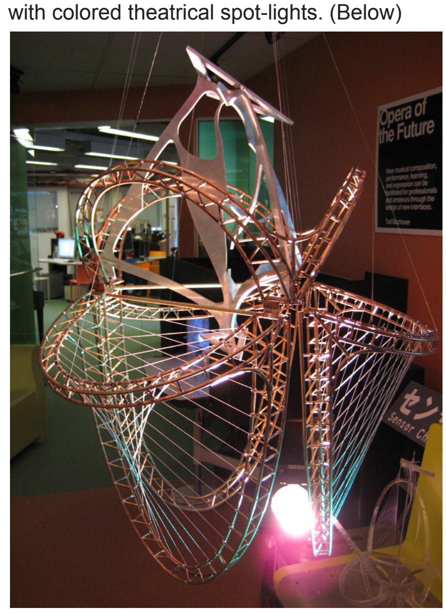


Figure 4.25 Motor drive system and electronics of the physical prototype.

Figure 4.26 Physical prototype being illuminated with colored theatrical spot-lights. (Below)



Perhaps the most satisfying result which emerged from the set-up and display of the physical model was the extremely powerful visual effects of the piece interacting with the intense theater spot-lights which is, of course, the correct kind of illumination to test the model. We used two medium sized theater spot-lights which were each equipped with a rotating color filter unit. This equipment would wash the model with constantly changing hues of intense color. For the very first time in the entire design process, the idea of a chandelier, a centerpiece which inspires attention through a composition of light and formal beauty, came to life within our design. A long standing question about the visual effects of the strings

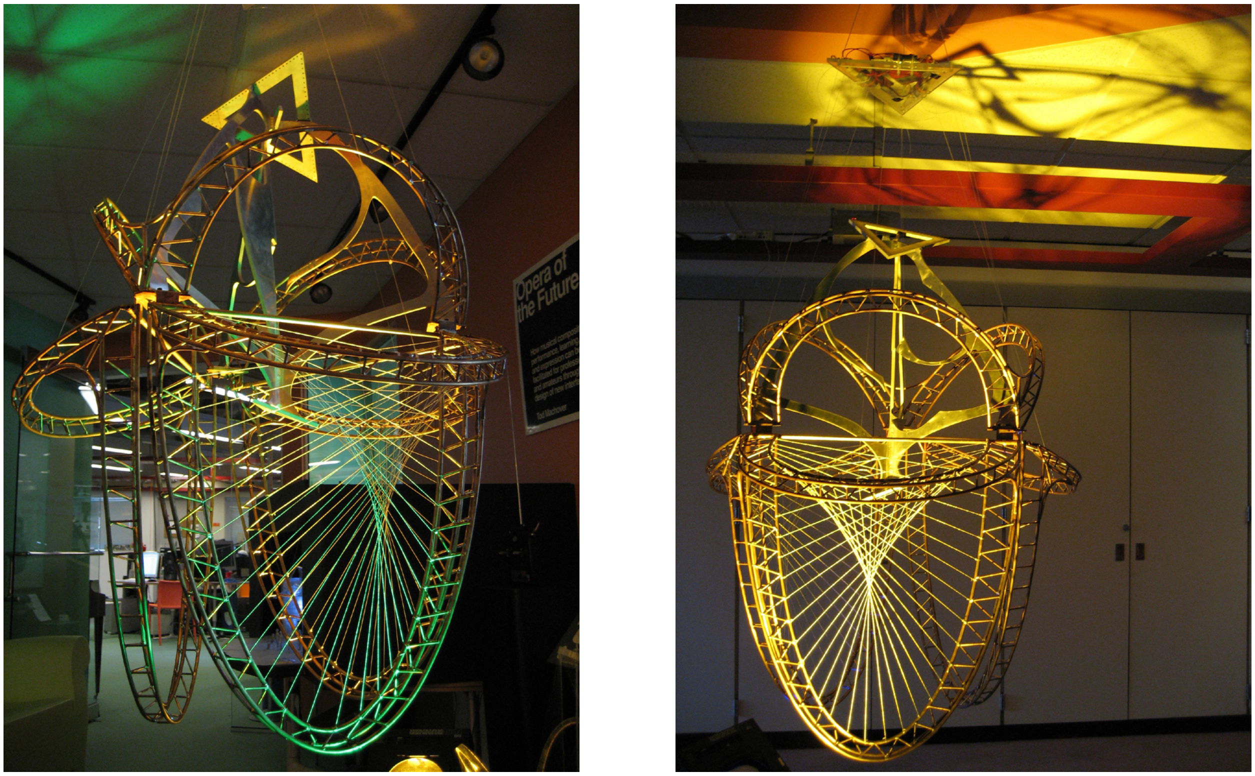


Figure 4.27 Physical prototype of the Chandelier under theatrical illumination.

was also answered. It had been an ongoing concern for us, from the very beginning, that the visibility of the strings at such a distance and scale would diminish to practically nothing when the full scale Chandelier piece would finally be put onto the opera stage. In normal lighting conditions, the very small diameter of the strings, despite the large number of them, causes their visibility to fade away very quickly with increased distance. If this was indeed the case, the perception of the piece would change radically from the intentions of the 3D CAD model which emphasized the string surfaces. The trussed arc elements and surfaced mass of the center would completely dominate the perceived form. However, under the illumination of the proper intensity provided by theater spotlights, the physical prototype proved that with the appropriate metallic, reflective finish of the strings, our visual perception of the string surfaces would indeed be very strong. This was a triumph, and could only be answered definitively with a physical prototype.

One unexpected, but perfectly welcome, outcome of the physical model was the compelling formal quality of the aluminum support structure. The original intention, of course, was not to have this be exposed at all. It is the skeletal support for the freeform shaped surfaces of the central form. However, the visual qualities of the aluminum curves, which are generated purely out of the demands of the shape of the central form, are compelling enough to stand on their own as a sculptural artifact of the entire process. The other highly interesting, yet accidental, aspect to leaving the aluminum exposed is a strange visual illusion which is caused by the freeform shape of the aluminum assembly being placed in the center of this particular triangular symmetry of lattice-like structure. This gives the visual impression or illusion that the solid metal aluminum center is transparent, and that one can see the trussed elements through the center at any angle of view. For these reasons, it was decided that the physical model could be left as is, and that the complete study of illuminating the central form could take place via ray-trace rendering studies in the 3D CAD environment.

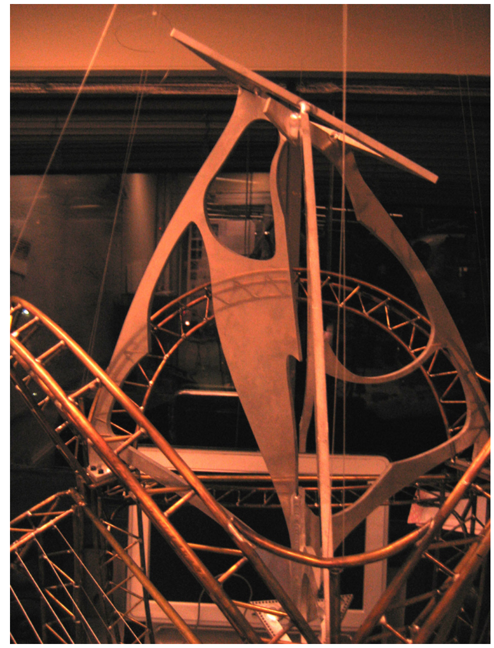


Figure 4.28 The central form skeleton of the Chandelier exhibiting a transparency effect caused by the unique triangular symmetry of the design.

4.6 The Geometry of Constructibility

One of the truly great advantages of using the 3D CAD medium for the design of sculpture and architecture, or anything else that will actually get constructed, is the ability of the medium to specify and drive the construction and fabrication processes with incredible accuracy. This is made possible by very robust mathematical models which define the geometry of the digital archetype. There have been many people involved in various industries that have helped to pioneer this relatively new way of designing, building, fabricating, and constructing things. Perhaps, one of the most significant figures to have made a major contribution to this new construction paradigm is the famous architect Frank O.

Gehry. For many decades, Gehry struggled with his unusual and geometrically challenging building designs. They were often prohibitively expensive to build, and he continued to imagine increasingly more complex geometries of a highly free-form nature. Eventually, against his initial feelings about computers, he began to experiment with high-end 3D CAD systems which had only been used for the design and engineering of airplanes and automobiles. He discovered that not only was he able to work out complicated design issues with this form of media, but he could now precisely specify the complete geometry of the design to the construction and fabrication sub-contractors. The barrier for actually being able to realize his imagined freeform, sculptural ideas in his architecture had finally been overcome. Because of the robust mathematical definitions which existed only in high-end 3D CAD systems like CATIA, the ability to realize geometrically complex structures at the scale of a building became possible. Many feel that Gehry's most significant contribution, long into the future, may turn out to be the inception of the "digital archetype" as a means to construction, even beyond his distinctive post-modernist architecture. Gehry, himself, has affirmed this sentiment with his own comments on the matter.

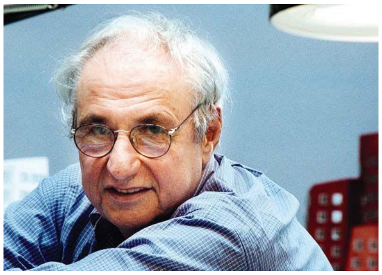


Figure 4.29 Frank O. Gehry, circa 1990.

4.6.1 The Math Required for Constructibility: NURBS

Probably the most common mathematical implementation used in 3D CAD today is the NURBS model. This is an acronym for Non-Uniform Rational Basis-Spline. While the mathematics of NURBS can become rather complex, a brief discussion of the advantages will be appropriate here.

Why use NURBS to represent 3-D geometry? The NURBS model has several important qualities that make it highly suitable for computer aided modeling. First, There are several industry standard ways to exchange NURBS geometry. This means that all parties connected with a project should expect to be able to move their valuable geometric models between various modeling, rendering, animation, and engineering analysis programs. They can store geometric information in a way that will be usable in several decades. NURBS have a precise and well-known definition. The mathematics and computer science of NURBS geometry is taught in most major universities. This means that specialty software vendors, engineering teams, industrial design firms, and animation houses that need to create custom software applications, can find trained programmers who are able to work with NURBS geometry. NURBS can accurately represent both standard geometric objects like lines, circles, ellipses, spheres, and free-form geometry like automobile bodies, people, and crazy buildings. The amount of information required for a NURBS representation of a piece of geometry is much smaller than the amount of information required by the faceted approximations of the same geometry.

Most low-end graphics software offers low-level geometric primitives for objects such as lines, points, and triangles. Because the representations of these objects are mathematically exact -- lines being defined by their two endpoints, triangles by their three vertices, and so forth -- their resolution is independent and unaffected by changes in position, scale, or orientation. These low-level primitives can also be used to define arbitrarily shaped objects, such as a vase or an automobile, but at the cost of these desirable mathematical properties. For example, a circle that is approximated by a sequence of line segments will change its shape when rotated. One of the advantages of NURBS curves is that they offer a way to represent arbitrary shapes while maintaining mathematical exactness and resolution independence. NURBS give you great control over the shape of a curve and are highly interactive. A set of control points and knots, which guide the curve's shape, can be directly manipulated to control its smoothness and curvature. They can represent very complex shapes with remarkably little data. For instance, approximating a circle three feet across with a sequence of line segments would require tens of thousands of segments to make it look like a circle instead of a polygon. Defining the same circle with a NURBS representation takes only seven control points! In other words, only the coordinates of the control points are stored as data. This is because the basis functions, which are defined by NURBS mathematical formulae, will precisely generate the geometry from this minimal data.

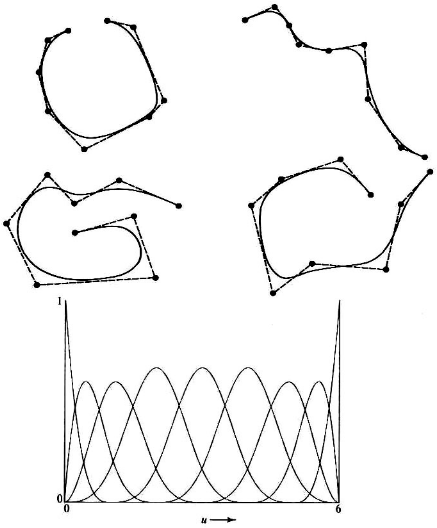


Figure 4.30 Examples of some NURBS curves showing the control point polygons along with the basis functions which determine their precise shape.

In addition to drawing NURBS curves directly as graphical items, one can use them in various other ways that exploit their useful mathematical properties, such as for guiding animation paths or for interpolating or approximating data. One can also use them as a tool to design and control the shapes of three-dimensional surfaces, for purposes such as surfaces of revolution (rotating a two-dimensional curve around an axis in three-dimensional space), extruding (translating a curve along a curved path), and trimming (cutting away part of a NURBS surface, using NURBS curves to specify the cut).

$$B_0(u) = \begin{cases} b_{-0}(u) = \frac{1}{6}\, u^3 \\ b_{-1}(u) = -\frac{1}{6}\, (3u^3 - 12u^2 + 12u - 4) \\ b_{-2}(u) = \frac{1}{6}\, (3u^3 - 24u^2 + 60u - 44) \\ b_{-3}(u) = -\frac{1}{6}\, (u^3 - 12u^2 + 48u - 64) \end{cases}$$

Figure 4.31 A third-degree set of polynomials which define the NURBS basis functions. Each basis function represents the amount of influence that a given control point will have over the shape of the curve. Therefore, only the control point data is required to precisely construct the curve at any resolution.

4.6.2 Rationalizing Geometry

In the process of the design and construction of a geometrically complex project, there comes a stage in which the project and all of its parts must be defined and exported in some way for the actual construction. There is a certain difficulty associated with creating the precise definition of every part. To begin with, the 3D CAD model may be constructed of many freeform surface elements which need to be broken down into constructible units. Then, the units must be made to conform to geometrical constraints which are determined by the properties of materials and other limits of constructibility. Generally, this means that the freeform geometry of the digital model must be analyzed and modified slightly in order to conform to those constraints. Theoretically, this shouldn't change the look or shape of the model as a whole. But there is a high level of craftsmanship in "rationalizing" the geometry of the model.

> Rationalization is the resolution of rules of constructibility into project geometry. ...The activity of selecting a digital representation for spatial system components -- in congruence with the physical constraints on the fabrication of these components -- is a core aspect of the rationalization process [Shelden 2002].

In this context, the term "rational" is meant in the sense of a ratio. It probably originates from the same place that the "R" in NURBS does [Watt 1999]. When the math that defines a given geometry is rationalized, the geometry gets modified toward a more canonic form, that is, a simpler form such as a conic, cylindrical, spherical, cubic, or planer form. By dividing the coordinates of the points that control the geometry by a number that represents a common dimension, the control points are converted to ratios, or "rationalized." As a result, the geometry is effectively projected into a space which is one dimension less than the space of the former geometry. As it turns out, by projecting the geometry in this way, the shapes of NURBS curves are allowed to be canonic in form.

In the case of the Chandelier design, much of the geometry is canonic in form and will therefore be less costly to construct and fabricate. It is always less labor intensive to fabricate a circular arc, for example, than a freeform curve, no matter what the material might be. However, the overall assembly and composition of parts in the Chandelier is much more complex from a construction point of view. And the abstruse geometry of the central form may at first appear exceedingly difficult to construct. In fact, the central form, though it may seem to be the most challenging element to fabricate and construct, will probably be easier than the rest of it. Why is this so? The

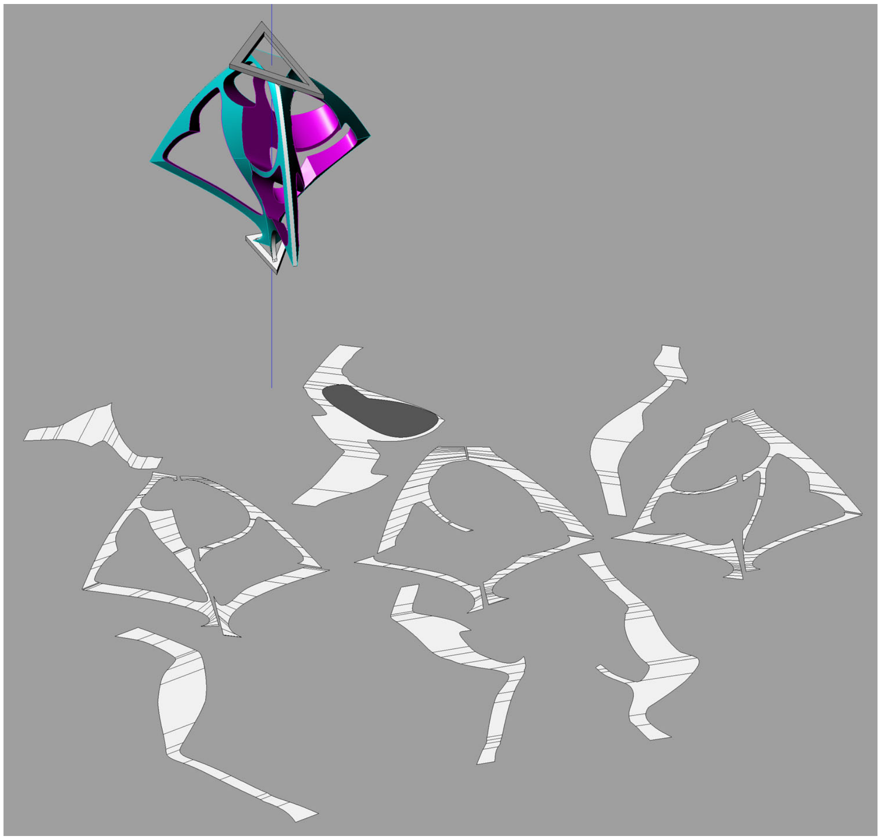


Figure 4.32 The central form made up of "developable" surfaces which can be unrolled to a completely flattened shape without any distortion.

central form, though highly freeform and organic in shape, is designed with very rational geometry. Specifically, all of the surfaces of the central form are of a special type called a "developable" surface. The geometry of this kind of surface is a special case of a ruled surface. A ruled surface is one that is curved in one direction, but is defined by ruling lines in the other perpendicular direction. The "developable" surface is a ruled surface that has the added geometric constraint that all of the surface normals along any given ruling line must be coplanar. In simple terms, the constraints of this geometry allow any surface of this type to be "developed" or flattened out onto a plane without any distortion. This is a behavior that many materials can conform to, and therefore is an ideal geometry for designing freeform shapes.

4.7 Building a Full Scale Mock-up of the Chandelier

During the one and a half year phase of conceptual design of the Chandelier, two principle courses of investigation took place. There was the evolution of the overall form which dealt primarily with artistic and aesthetic issues. In tandem with that was the development of a full scale mock-up of one of the "wing" sections of the piece. The primary purpose of the

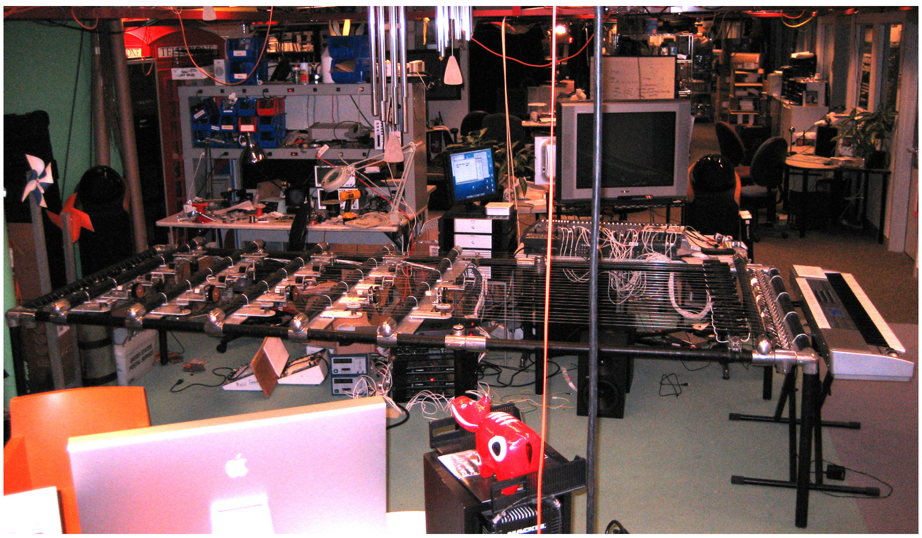


Figure 4.33 Full-scale mock-up of the Chandelier at the Media Lab.

mock-up was to design and test the electromechanical system that would interact with the strings to produce musical sound. As mentioned previously, my primary responsibility was the former and Fabio's primary responsibility was to engineer the system and mock-up. In this section, I will only briefly discuss the system and mock-up giving emphasis to my own prototype for an interface to the system. For a thorough treatment of the sound production mechanisms and robotics associated with the system, the reader is referred to Fabio's recent Masters thesis on the topic [Fabio 2007].

4.7.1 Design and Proof of Concept

It was determined relatively early in the design phase that the

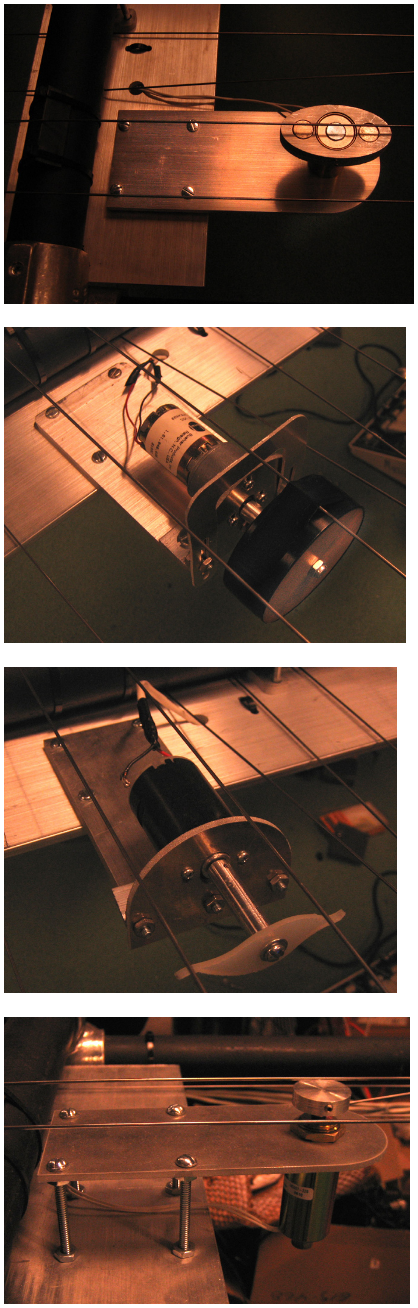


Figure 4.34 Various solenoid and motor actuators installed on the Mock-up.

size and scale of the Chandelier was going to be relatively large with respect to the rest of elements of the set. The height of the piece would be between 12 and 14 feet. As a result of this, it was calculated that the longest strings would have to be about 12 feet in length. Initially, Fabio, two UROP assistants, and I began to experiment with various ways to generate sound from a very long string. Soon, Fabio took the lead in developing a large steel frame which would be able to support the tension of about 25 to 30 long strings of piano wire as well as a complete series of mounted solenoids and motors that were set up to excite the strings with various attachments. These attachments consisted of an original version of a rosin wheel, several rotating rubber "weed whackers," and a series of solenoid hammers which would directly hit the strings. There were also a number of electromagnets which would induce a resonance purely by a changing electromagnetic field.

One very important fact to note about the sound creation of the Chandelier, and hence, the mock-up, is that all of the sound is produced physically. That is to say that what is actually heard is the physical vibrations of the strings which are then fed into electronic pick-ups that subsequently get amplified in a standard sound reproducing system. There is no electronically created or synthesized sound in the Chandelier.

4.7.2 Beyond the Keyboard: An Alternative Interface

During the development of the mock-up, Fabio and I extensively discussed and began to experiment with various ideas for interfaces to control the production of sound in the Chandelier. While none of the ideas were developed to the extent that they became a permanently established component of the Chandelier instrument, we were able to develop a couple of prototypes that proved to be quite interesting. In its current state, the mock-up uses a standard electronic MIDI keyboard as the human interface to the instrument. However, Fabio and I each developed an alternative interface as a shared effort to depart from the keyboard approach.

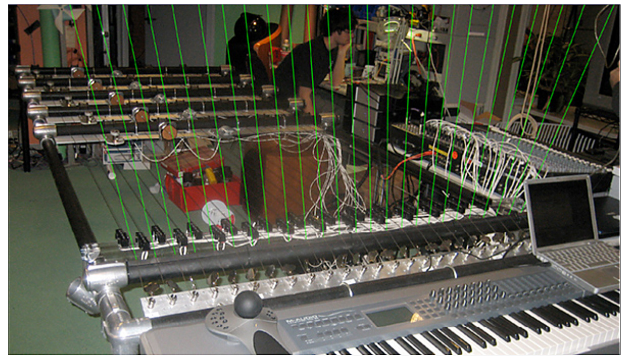


Figure 4.35 Mike Fabio's conception of the laser-based human interface to the Chandelier. (Concept image by Mike Fabio)

Fabio's interface design centered around the idea of an array of laser beams similar to the string arrays which form the implicit surfaces of the Chandelier. According to Fabio, the user can have two dimensions of control by waving the hand through the laser beams. The horizontal movement of the hand passing through the beams might control different actuators or "pitches" of the instrument. The vertical movement of the hand could be mapped to an intensity or volume parameter of the sound. Fabio is quoted here:

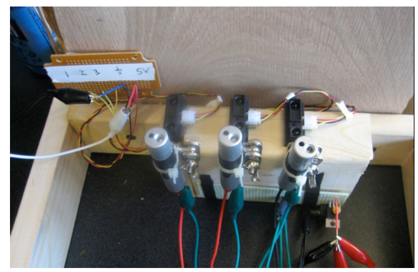


Figure 4.36 Three-laser working prototype of Fabio's interface. (Photo by Mike Fabio)

> While synthesizer mappings are entertaining and useful, the real purpose of building the laser harp was to control the Chandelier. It was always my intention to physically integrate the visual language of strings into both the instrument and controller, essentially extending the strings of the Chandelier into vertical space as lasers. And although I was never able to build a 25 string model, the three string model is remarkably good at controlling the Chandelier [Fabio 2007].

My own proposed design for a human interface to the sound control of the Chandelier is based on a spherical controller device which was, ironically, engineered for the 3D CAD industry. Normally, the device is intended to manipulate 3D models within the space environment of a number of high end CAD systems. The controlling device is a stationary rubber ball that contains a very sensitive mechanism which has six fully independent degrees of control corresponding to how one can manipulate such a ball. That is, translation along the X, Y, and Z axis as well as three degrees of rotation about each axis. The

Figure 4.37 3D Connexion *Spaceball* used for the spherical control interface to the Chandelier.

response is super sensitive and really does not require that the hand physically displace the ball beyond a few millimeters if even that. This characteristic then provides the potential for an extremely responsive musical controller if strategically applied and mapped to the musical parameters of the Chandelier.

The 3D “Space Ball”, as it is called, was developed by 3D Connexion, and was really designed to “sense” what the hand wants to do rather than to be moved or manipulated by the hand. The basic problem initially was to develop a software interface that would allow the Space Ball to communicate with various musical parameters of the Chandelier mock-up. It was given that the interface would have to use the MIDI protocol since Fabio had set up the interface to the actuators of the mock-up to use the protocol. I chose the Max/MSP development environment to develop the interface, because it offers many objects in its libraries for controlling and manipulating MIDI messages. The first problem was getting Max to see and accept the data coming from the Space Ball device. Because the device has been engineered to be dedicated to specific CAD applications, Max did not see this data due to the limited ability of the low-level drivers which provided the interface between the Space Ball and the operating system. Subsequently, I contacted the manufacturer, and fortunately, they put me in contact with a person in development who had been working on more ‘generic’ drivers that would give general access of the data for most purposes, and he most graciously allowed me to take and use these beta drivers after I had explained my research application. Once the drivers were installed, Max was then able to read and accept the data. However, this data was of a proprietary and odd form. I developed a series of Max patches which would,

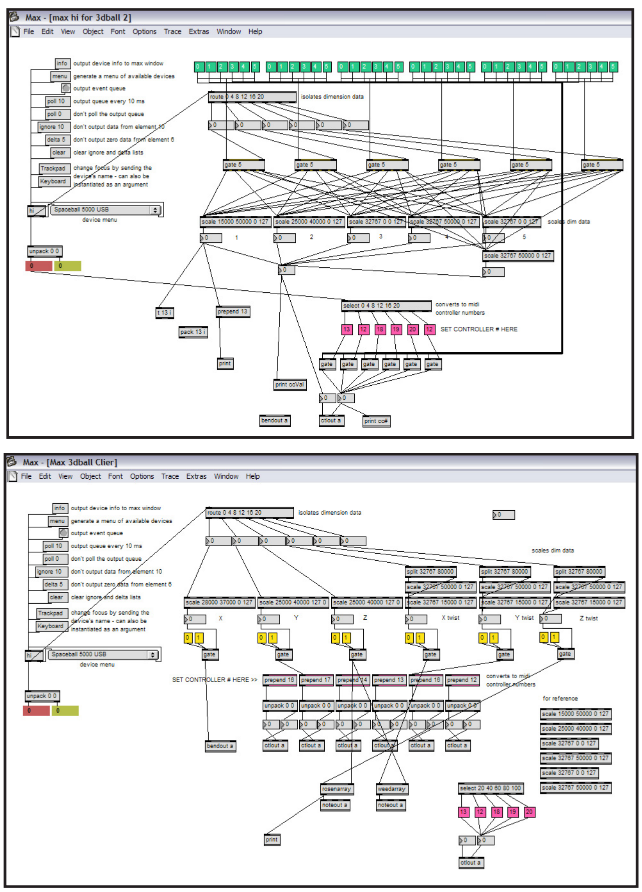


Figure 4.38 Max/MSP Program code for the spherical human interface controller. (See Appendix A for a detailed image)

first parse the data to make it useful, and then separate the very large numerical packets into the respective six streams of dimensional information. Once there were six distinct data streams, the large numbers had to be translated into useful MIDI code, namely into logical controller and pitch messages; and then, of course, be sent out of the computer through a MIDI port.

After the main problem of developing a Max interface to allow the device to communicate MIDI was complete, I was then able to turn to the challenges of mapping the six available dimensions to appropriate, expressive, and meaningful musical parameters with respect to the Chandelier. The Space Ball worked very nicely to integrate the control of these parameters so that there was a kind of "oneness-like" character to the feel of what I was controlling. After much experimentation with different mapping configurations, certain principles seem to emerge. First, as it turns out, it would seem that certain dimensions are somehow more intuitively useful and perhaps more natural to use than others. For example, I found that rotation or twisting about the Z axis was perhaps the most natural of the rotational dimensions for movement of the hand. It is both easiest to visualize and perhaps the most immediate movement that the hand will tend toward. Therefore, it seemed only reasonable to assign that dimension to an important parameter of the timbre manipulation. Taking that idea further, I found that it was useful to establish a hierarchy of importance to all parameters with respect to their function in the resultant sound, and then to map the dimensions according to how the most natural and intuitive motions would align with that hierarchy. There was also the question of how many dimensions to actually employ. It became clear to me very quickly that using all of the six dimensions of the ball would neither create the most interesting or musical result, nor would it make things easier to control. In fact, it often appeared that even just two or three active dimensions would give the best, most approachable and most interesting mapping configurations. It also seemed easier

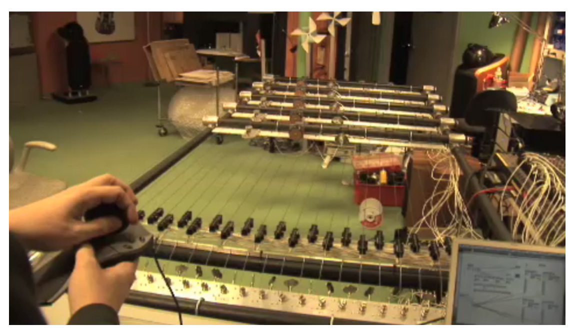
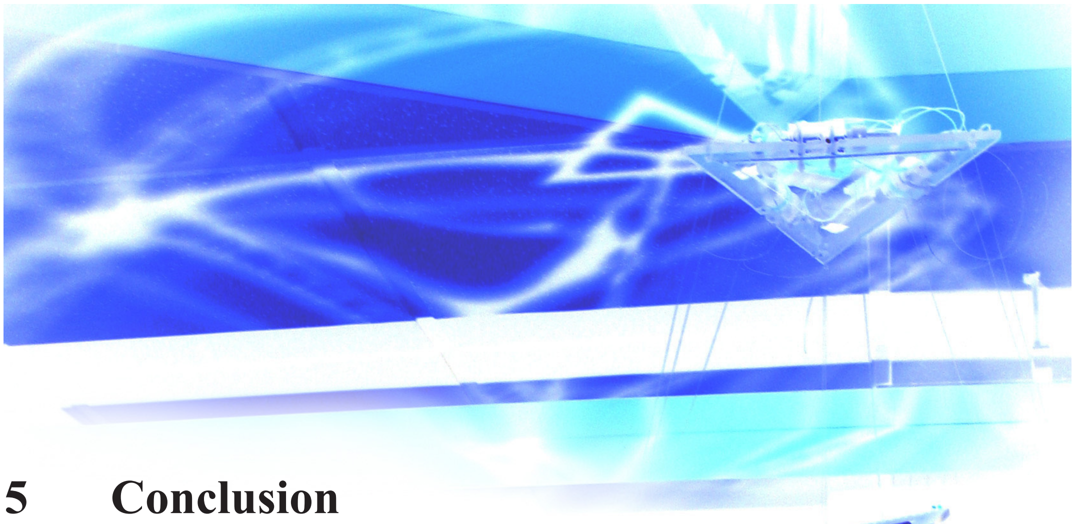


Figure 4.39 Spherical interface controlling the Chandelier mock-up.

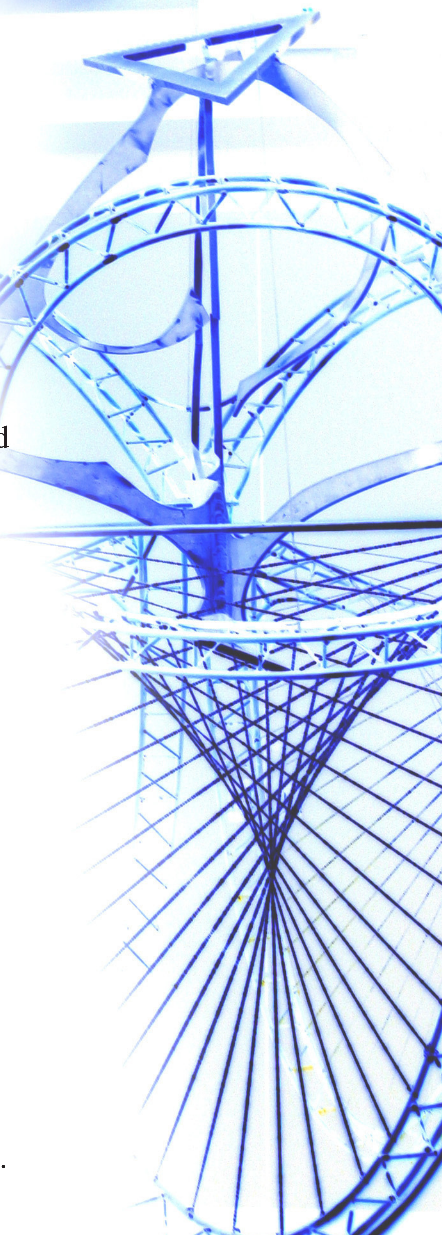
to intellectually grasp what was happening with the relationship between the user's hand movements and the resultant sound. After the Z axis rotation, it seemed that simple translation along the X axis was the next most intuitive way to manipulate the ball, and then perhaps the Y and Z translation dimensions would follow after that.

The Chandelier presented unique problems when it came to implementing a control strategy for the Space Ball. As previously discussed, there are many sound producing mechanisms. Thus, one significant challenge was to decide how to use only six dimensions of control to effectively give adequate expression to the ball. Despite the preceding discussion, I ultimately decided to use all six dimensions. Two were assigned to the rosin wheel array and the weed whacker array respectively. One was assigned to the initial intensity for both arrays. One was assigned to the pitch of the sign wave electromagnet, and another to the amplitude. The last one was assigned to the real-time intensity control of whatever was making sound at any given moment. This combination proved to be very effective at giving a full range of expression to this multi-faceted musical instrument.

Working with the Space Ball as a controller for the Chandelier as well as a general music controller has given certain insights into the possibilities of the device for such applications. One advantage of the high sensitivity of the ball is that the ergonomic conditions allow the user to work with it for very long periods of time. Any musician knows that to practice an instrument for many hours gets into strain issues. This device would help minimize such strain with extended use. Also, physically impaired persons may be able to make wide use of it for many music generating applications. In my opinion, the most unique aspect of this device is that it feels and handles like a completely integrated singular control even though there are six dimensions to it. That is, you never feel like you are controlling six different things. I imagine that there could be far more subtle applications which might use samples to emulate very realistic and natural sounding musical instruments.



Chapter 5 Conclusion



5.1 Results, Successes, Failures: An Evaluation

This thesis represents an explorative investigation into the design of a central set piece for a new science fiction opera that promises to be on the vanguard of art and technology. The Chandelier is several things. In this thesis, it has been presented as a work of kinetic sculpture, a major set piece for the *Death and the Powers* opera, a newly invented kind of musical instrument, and ultimately, the subject of an exploration into conceiving an authentic digital form. By implication, the proof of its authenticity would be a form that is difficult or impossible to conceive outside of the digital medium. However, I would like to make the point that for a form to be authentic in this way, i.e. to be a “native” conception of the 3D CAD medium, it would not necessarily require that it be complex or inconceivable by other means. Rather, complex geometrical ideas and abstruse form have been the domain of my particular interest in this work. And one of the primary challenges that I have defined in this thesis is that of realizing such a form in the Chandelier project while at the same time succeeding in rigorously specifying the design for construction.

But the fundamental problem set forth in this thesis was to achieve a balance in satisfying the many varied requirements that were imposed on the Chandelier project. These requirements included those that I have imposed myself. Henceforth, the only real method of evaluating the Chandelier at this stage would be to ask the following questions:

1) Is the design a compelling piece of kinetic sculpture?

2) Does the design function well as a central set piece for the opera?

3) Is the design successful as a new kind of musical instrument?

4) Has the design successfully created an object in which the behavior augments expressive understanding of music being performed?

5) Is the design one that could be considered authentic to the 3D CAD medium, and beyond that, conceivable only in that medium?

6) And finally, is the design actually constructible?

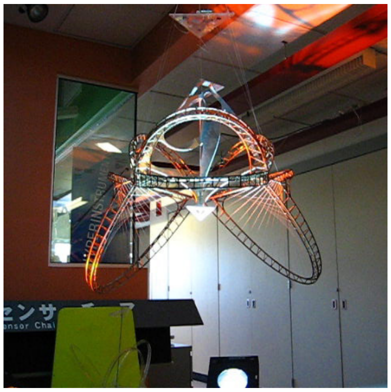
5.1.1 Development

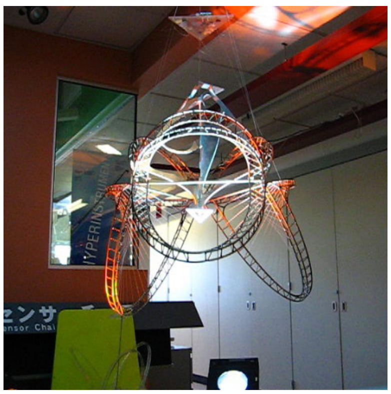
The Chandelier has been in development for about one and a half years. The process of collaboration during that time has played an essential part in the influence of its evolution. Much of the struggle with pushing the development of the design forward has had to do with the management of many functional demands and varied interests that were all pulling in different directions. As we would focus our work on one particular area for a while, it became very easy to neglect another. For example, during the summer months of 2006, we put most of our efforts into researching and developing the Chandelier as a musical instrument. In the meantime, we let the aesthetic development of the design fall somewhat by the wayside. When we returned to the aesthetic side again in the Fall, it seemed as if there was an incongruity that had developed. That is to say, it was almost as if we were suddenly developing two different, somewhat unrelated projects. This experience served to underscore the fact that every aspect of the project should be developed simultaneously in the interest of achieving an integrated and well-balanced design. Perhaps, the greatest reason for that would be the observation that each area of development continually and constantly informs the other.

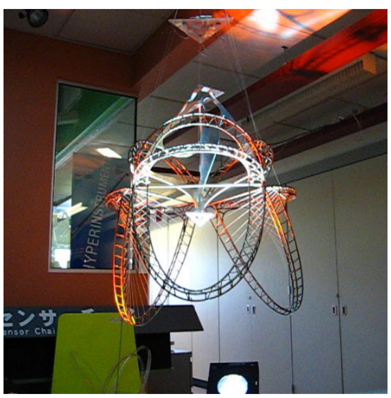
The construction of the quarter size physical prototype at the end of the design period became the proof of concept in many respects. In this thesis, I will use it as a basis for evaluation of the design. Many of the outstanding questions that had been looming during the evolution of the design within the 3D CAD environment found answers with the completion of the physical prototype.

In comparing the physical prototype with the digital archetype, the question of whether the Chandelier design was successful in realizing a digitally authentic form or not comes immediately to the forefront. If one considers only the symmetrical outer frame of the piece, it is primarily composed of rational geometry consisting of parabolic and circular arcs. These arcs are assembled in a triangular configuration which is readily understood and palpable. Even though there are subtle, continuous variations in the size of the transverse sections of the structural arc elements, the frame, taken by itself, would easily be designable with a standard drawing board. However, if the entire piece with the abstruse central form is considered, then, the piece as a whole becomes a much stronger case for an authentically digital conception. Since the creation of the central form actually began with converting an envelope of empty space into a volume, the piece immediately moved into another conceptual domain. After several iterative stages of Boolean transformations, the form and its relationship to the rest of the piece became a conception that was only possible through the 3D CAD medium. For this reason, I believe that the design did achieve some degree of success as an authentically digital conception.

5.1.2 Aesthetics

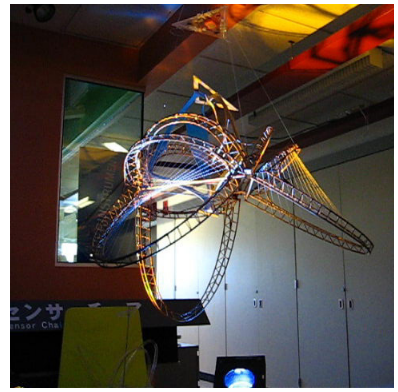






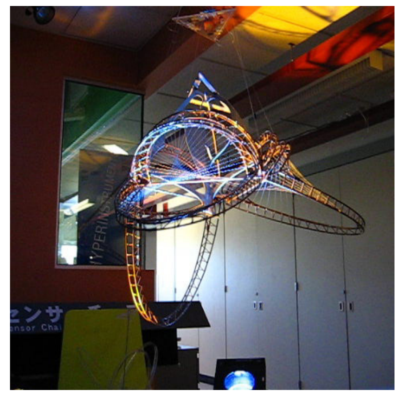
With regard to the Chandelier as a kinetic sculpture, many of the students, faculty, and visitors to the Media Lab have responded quite favorably to both the physical prototype as well as the digital model. However, one of the greatest successes that came from testing the prototype with the actual illumination that will be used in a theatrical setting, was the sudden magical presence of the otherwise barely perceptible layers of strings. Even with such a small diameter, the form of the implicit surfaces articulated by the strings really came through as a result of the intensity of the spot-lights. This particular quality would have been virtually impossible to prove with rendering technologies in the 3D CAD environment. One result of this important achievement was the verification of the dynamic visual energy emanating from the moiré patterns of the string surfaces. As predicted, it only required a small amount of subtle rotational movement in the wing sections to produce a massive moiré effect. Although, this effect was not always present and would occur more intensely at certain angles of view and points in time.

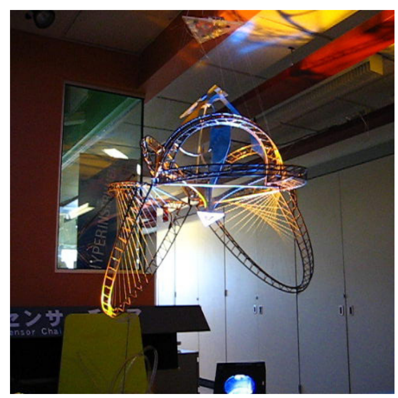
The wing sections of the Chandelier were successful in functioning with their intended movement in the physical model. The real success here was the demonstration of complete physical stability while the piece was suspended during the independent movement of all three wings. Even sudden, radical movements through the entire rotational range did not destabilize the piece in any way. However, I was not able to test the interactive lighting effects on the central form as I had emulated with the digital lighting studies shown in section 4.4 of this thesis. Therefore, the physical model did not contribute any proof of concept with regard to this issue. Without this dimension to compliment the movement of the wings, the mechanical motions of the wings alone held an observer's interest only for a limited time. Overall, the relative successes shown from the tests of the physical prototype make a fairly strong case for the piece as compelling set element for the *Death and the Powers* opera.



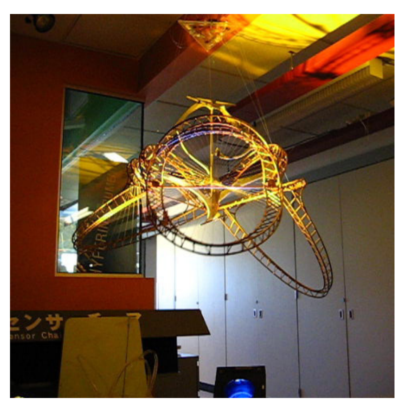
5.1.3 Technology

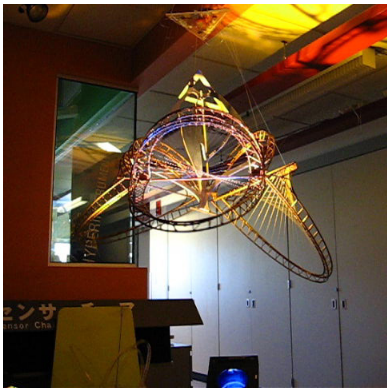
Perhaps, the most difficult questions to evaluate are those related to technology. This is mostly due to the fact that much of the technologically related issues have, ultimately, yet to be tested. The real test of the technology will come with the completion of the actual Chandelier. We have constructed a physical prototype model which is one quarter of the size of the full scale piece. We have also constructed a full scale mock-up of one of the wing sections. Both of these have helped inform us about what many of the actual physical conditions and behaviors will be with regard to the final piece. Also, they have enabled the testing of several notions and theories. And yet, perhaps the greatest question still remains: Will the current design of the Chandelier be a viable, compelling, inspiring, functional musical instrument? Ultimately, that is very hard to say for sure. The mock-up proved to be an interesting and effective instrument in its own right. The sonic textures were very evocative and utterly original. But the mock-up is somewhat removed from the setting and context of the opera. If it represents just one wing section, there remains an important question about how the complexities of three of these elements will work together and interact with the rest of the piece as a whole.

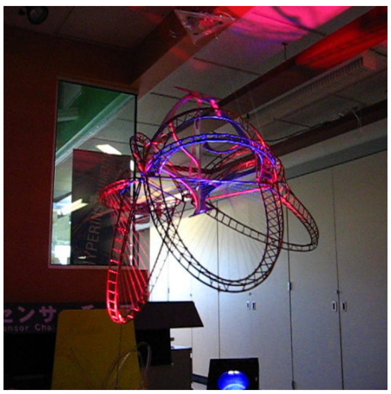


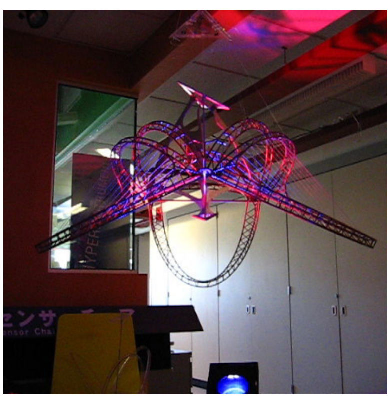


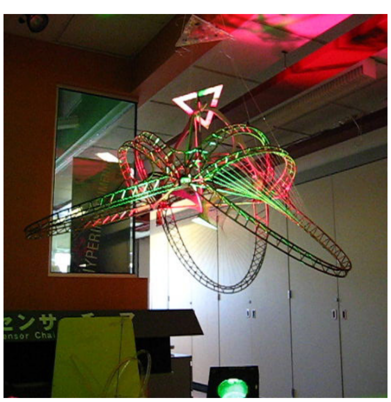
The physical prototype made great strides forward in demonstrating structural integrity and mechanical function as well as several aspects of aesthetic quality. But it contributed nothing to informing us about the Chandelier as a musical instrument. Therefore, at this stage, we have a mock-up and we have a physical prototype, but we don't have anything close











to a fully integrated musical instrument. There are, as yet, so many questions about what the global effects might be of a mock-up element multiplied by three and the number of strings multiplied by six or seven all positioned in close proximity. The only way to answer these questions will be to build a full prototype and see what happens.

As far as the last question of constructibility is concerned, the 3D digital archetype can go a long way in helping to predict the likelihood for the successful construction of the project. However, the physical prototype was necessary to actually test the physical behavior of the materials, mechanics, and structural integrity of the final design. In this sense, the proof of constructibility was demonstrated to a great extent. However, there were certain physical parameters which were not accurately represented in the prototype. The decision was made to leave the aluminum skeleton of the central form as is, primarily because of the appealing aesthetic character. As a result, the exterior surfaces of the central form were not fabricated and assembled in the prototype. Due to the fact that every surface component was made to be developable, there is a very high degree of confidence that the assembly of the surfaces would present no problems. Given the time, that would be the easy part.

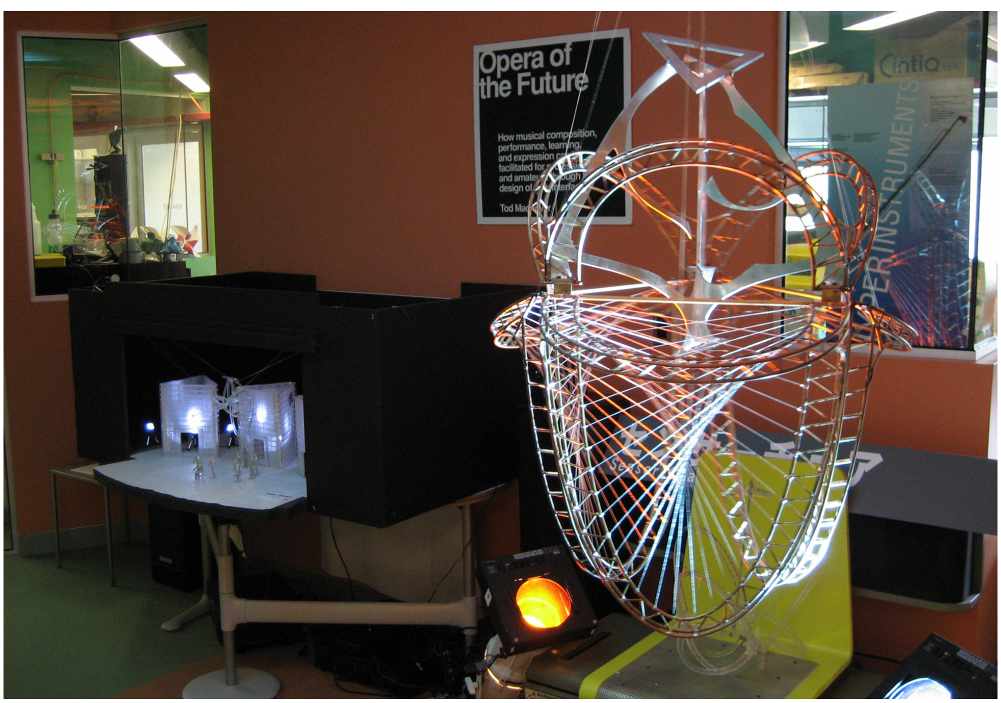
The material used for the outer frame was brass, but the most likely material to be used for the full scale piece is aluminum. Only the skeleton of the central form was fabricated out of aluminum in the prototype. Also, the strings used were metallic, but were not tensioned to an extent that would be comparable to the real conditions of a full prototype. The difference in these parameters does leave us with some uncertainty about the final construction. Ultimately, a full structural analysis will need to be done by an engineering consultant to insure the feasibility and safety of the final construction.

Finally, the only remaining question, of the six posed at the beginning of this section, asks if the Chandelier, as a visual object, behaves in a way that augments expressive understanding of music in performance. Because of the fact that the related research needed to conclusively answer this question has not happened yet, we can only speculate about the possibilities for behaviors that would augment such understanding. For this reason, several of such speculations are offered in Section 5.2 on future work.

5.1.4 Reaction and Evaluation During Sponsor Week

During the last sponsor week event in May of 2007, we had the first opportunity to suspend, test, and display the quarter size physical prototype. The general reaction to the model was very positive. It was installed and hung right at the entrance corridor of the Opera of the Future group next to an illuminated model of the set; and there was Tod Machover's music of a fifteen minute excerpt from the *Death and the Powers* opera playing

Figure 5.4 The physical prototype of the Chandelier and set design model during Sponsor Week.



in the background. The model was illuminated with two high-luminance theater spot-lights which were both equipped with a rotating color filter unit. As a whole, the entire display gave a strong sense of the theatrical setting of the opera and the proper sphere for which the Chandelier was intended.

I interviewed several people individually about their thoughts and reactions to the piece as a central element in the set of the opera. The overwhelming consensus was that the Chandelier was quite inspiring and functioned well as the embodiment and symbol of Simon Powers and his metamorphosis. One individual, who is an urban developer and architect from St. Louis, conveyed very serious interest in building a full-scale piece (without sonic functionality) for a large atrium space in one of his current building projects.

There were often large groups of visitors, faculty, and students who would gather around the Chandelier. We set up the piece so that the wing sections would move independently through a remote radio control device. The general reaction to the movements and reconfiguration of shape was almost always that of surprise and delight. Perhaps, the most satisfying observation that I made was to witness several people standing next to the piece studying it very carefully while it wasn't actually moving or doing anything at all. Many of them would stay for a long time just to stare at the piece. This was most gratifying and affirmed something that I had hoped for; the piece was being interpreted as a work of art.

5.2 Future Work

There is much to be done concerning almost every aspect of the Chandelier. Designing the piece represents over a year and a half of intensive development, and despite that fact, it is fair to say that it is still a work in progress. There is still quite a bit of room for continued exploration and research into the possibilities for inducing sonic timbres in the long strings. There is also the possibility of introducing other completely different schemes to create interesting sonic results which wouldn't necessarily have to have anything to do with the strings. It still seems that the possibilities are practically endless with respect to this dimension of the project.

The Chandelier has the capacity of movement, both mechanically and through light interacting with surfaces. But the question of exactly how these capabilities can be used effectively in a choreography to enhance a musical performance is an area for further investigation. Despite a great deal of thinking about these aesthetic issues of coordination, nothing up to this time has actually been modeled in the context of a live music performance. Thus far, we have set up the control of the physical prototype using a standard off-the-shelf radio control device to directly puppeteer the motion. We have not yet implemented any kind of intelligent control or animation technologies that could express programmatic or musical sequences.

The possibilities for how the choreography of the Chandelier could work are constrained only by the aforementioned capabilities. Since the development and implementation of the specific choreographic behavior has yet to happen, the brief description of these actions are provided here for completeness and the purpose of documenting the full conception of the Chandelier. This thesis would not quite be complete without, at least, a summary of the major ideas that have been percolating about such choreography, even if they are largely speculative at this point.

In order to facilitate an affective and meaningful choreography for the Chandelier, the functionality would have to include an interface to software that would be capable of following a musical score or other programmatic information. This timing information could be sent to the instrument so that the movement of the wing sections as well as the shape mutation of the central form could respond in a precise, temporal manner. The precision would have to be adequate enough to align with the "expressive cues" of tempo changes, articulation, and dynamics happening within the opera.

The wing sections could be programmed to move in a way that would echo the tension and energy or the harmonic resolve of the musical content. For example, as the music might build up to a level of tension through harmonic dissonance or sustained tremolo, the wings could reflect this visually through a coordinated succession of fast, very small back and forth movements which would convey a tremulous, vibrating feeling. Much like the gestures of a human dancer, the Chandelier could assume several different kinds of postures that would constitute its own kind of body language. This language would get established during the course of a performance and would develop the "character" which the audience would come to identify with. There are several positions or postures which the Chandelier can assume that naturally convey certain attitudes. An example of this would be the position in which all three of the wing sections are in agreement with gravity. In other words, they would all hang straight down in the closed position. In terms of body language and gesture, this is certainly an indication of repose. On the other hand, the completely open position, in which all three wings are in the upward, horizontal configuration, conveys an attitude of tension, because there is a perception of energy expenditure which must be maintained to hold the wing sections in that position. This becomes another syntactical element of the body-language grammar. Just as human dancers depend on such gestural language to convey mood that corresponds with musical material, the Chandelier would also, in that sense, depend on its own gesture of the body.

The mutational shape changes which are affected through the controlled illumination of surfaces can also contribute profoundly to the sense of body and gesture of the piece. There is probably a greater expressive range in one sense; the ability to control and change the direction and intensity of the wing-mounted spot-lights allows for very quick expressive gestures. The rotational movements of the wings are limited in the speed that they can move because of their size and weight. But the central form is able to execute very elaborate, expressive changes quite quickly. The increased speed of this action will allow a very precise visual alignment with musical cues. The perceived shapes could visually grow, mutate, extend, shrink, and explode in coordinated rhythm with the music. In this sense, it begins to resemble the spirit of a color organ. However, this would be a three dimensional object changing in form just as a dancer would; and as the Chandelier can easily reveal all angles of itself, the central form would be experienced as a dynamic physical object which responds in real-time to the surrounding musical environment. This, of course, extends far beyond the capacities of typical color organ.

Another area of research which we were only able to touch on is that of interfaces to the Chandelier. We developed a laser based human control interface as well as spherical based hand control interface. In both cases, they may prove to be worthwhile schemes to develop further. Much more could be explored with the specific problem of mapping parameters to the mechanisms responsible for sound. There is also very good reason to experiment with other possible interface schemes. As the final Chandelier instrument gets constructed, there is no doubt that other demands related specifically to the needs of the opera, as well as further technical requirements, will prompt further investigation into unique interfaces and means of control for the piece.

Perhaps, the area that is most in need of further development is that related to the integration of all of the research that has taken place. The mock-up has enabled much advancement in the sound creation system. The 3D CAD model has advanced the form and structure of the Chandelier design. The design and planning of the set and other aspects of the *Death and the Powers* opera has progressed to a relatively advanced point. What is probably demanding further research and development, perhaps more than any other single aspect of the opera design, is the integrated planning and synthesis that would bring all of these areas together to formulate a more global strategy. This most certainly means that the final construction of the Chandelier will be greatly informed by such a strategy. Building the piece, in itself, will begin to answer many questions about how it will function in the larger context of the set. As the opera gets closer to fruition, the full integration of all of the components will be necessary to uncover which technologies, interfaces, and designs will be the most useful and relevant, and which of them will not.

5.3 Final Thoughts

The experience of working on the design of such an exciting and futuristic opera has had many wonderful rewards. I feel extremely fortunate to have had the opportunity to take part in a collaboration with so many highly accomplished and esteemed personages in their fields. In this respect alone, I have learned an enormous amount. It has also been a very humbling experience to be around, and working with, such talented people. Before coming to MIT, I had the wonderful opportunity to work many years for the great architect Frank Gehry. This was also a humbling experience. However, through the years, I was eventually able to identify and move into an area within which I could become passionately active and make a valuable contribution. I am quite fortunate to have been intimately involved with developing the complex technology that enabled Gehry to construct his extremely challenging designs. Essentially, I became a key participant in bringing together unrelated, peripheral technologies, such as advanced 3D surface modeling utilized only in the aerospace industry at the time, to develop methods which greatly advanced the practices of the AEC industry. Such methodologies included more sophisticated techniques for digitizing physical models, computational applications for solving and automating complex design issues, and strategies for the complete, seamless integration of traditional 2D practices with the inception of the 3D digital archetype. I am both gratified and intellectually satisfied that I was able to bring some of that background to the work of this thesis.

One of the most important motivating factors in this work has been my passion for bringing the fine arts and technology together in a meaningful way. I have a very strong conviction that the development of the Chandelier, and the *Death and the Powers* opera in general, has made a significant contribution in serving that end. What remains now is my great hope that I will be able to witness the full realization of the art and technologies developed for the opera, the actual production of the opera, and the ultimate construction of the Chandelier.

Figure 5.5 Rendering of the complete set with Chandelier and Opera-bots.

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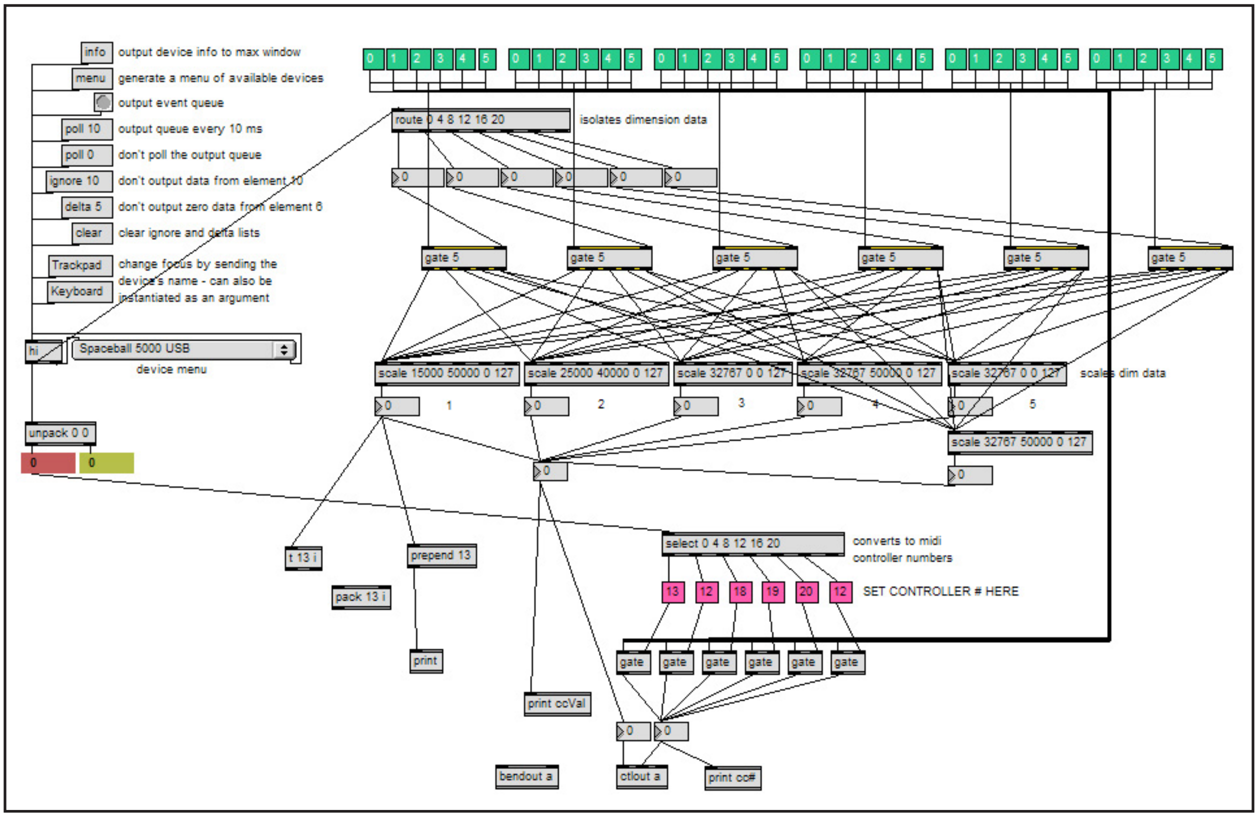
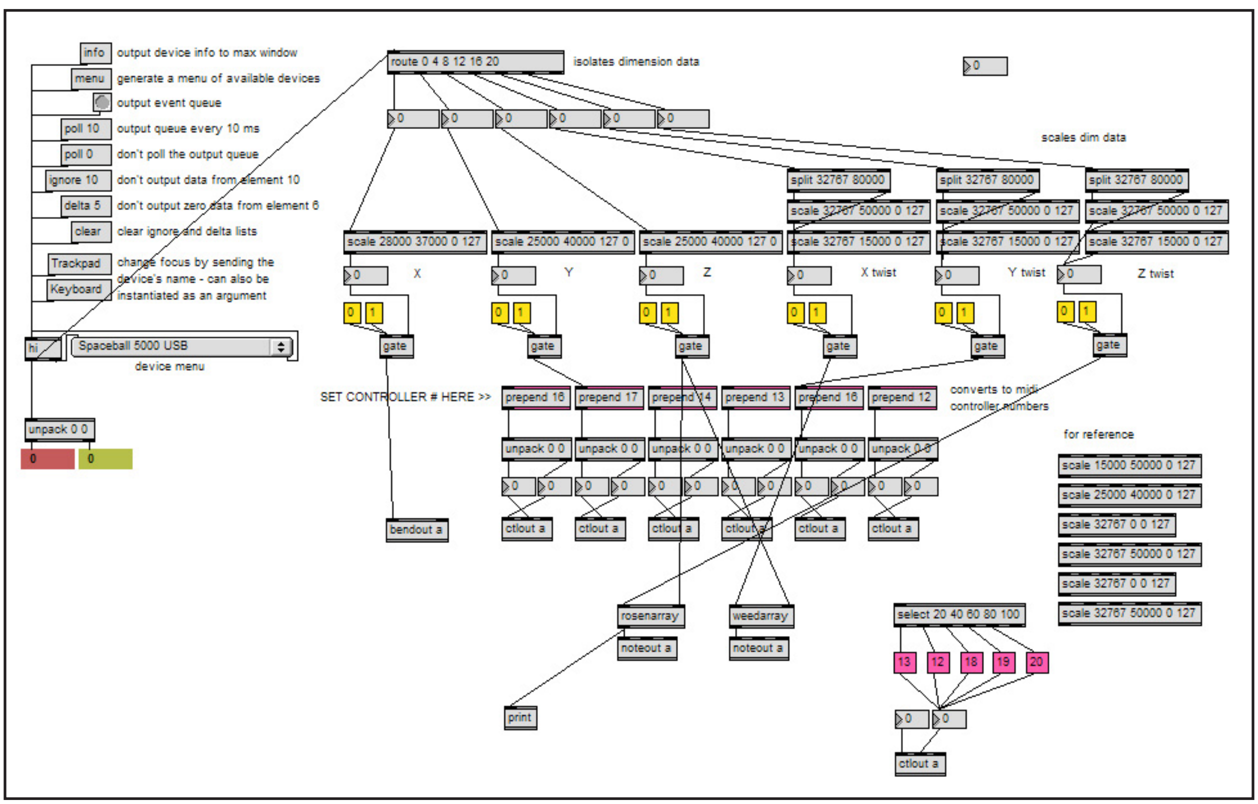
Reader Biography

Alex McDowell

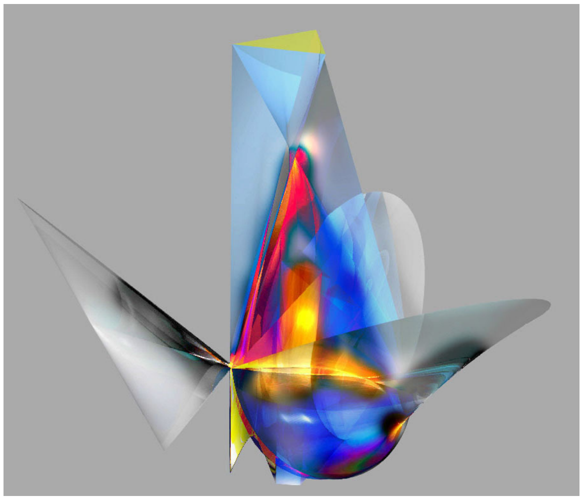
Alex McDowell, for 20 years a design leader in several pop culture fields (including record sleeve graphics and MTV videos), is currently most fully employed as a production designer in Feature Films. Born and trained in London, he moved to Los Angeles in 1986, having designed over a hundred music videos, and began a new career as production designer for many of the most cutting-edge young directors in commercials. In 1991, McDowell was called upon to production design the virtual reality cult film *The Lawnmower Man*, followed by *The Crow*; *Fear and Loathing in Las Vegas* with director Terry Gilliam, Fight Club with director David Fincher, *Minority Report* and *The Terminal* with director Steven Spielberg, and *Charlie and the Chocolate Factory* and *The Corpse Bride* with Tim Burton. For *Minority Report*, McDowell established the first fully integrated digital design department in the film industry, enabling the strands of 2D and 3D design, set construction, camera, prop manufacturing and post-production VFX to be efficiently linked and managed by the Design Team. McDowell is the founder of the revolutionary design and engineering think tank known as 'matter'. *Death and the Powers* is his first opera project.

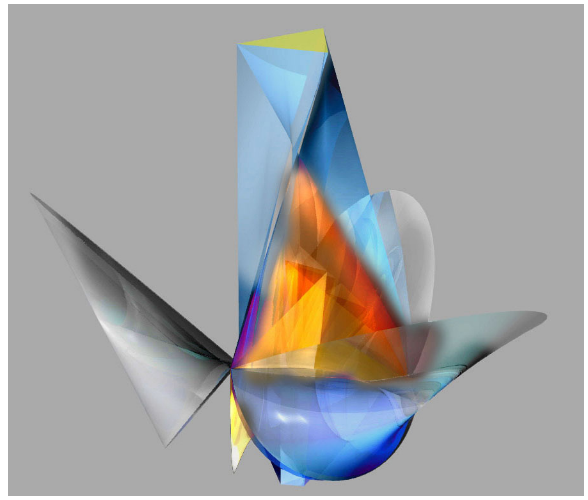
Appendix A: Max/MSP Code for the 3D Sphere Interface

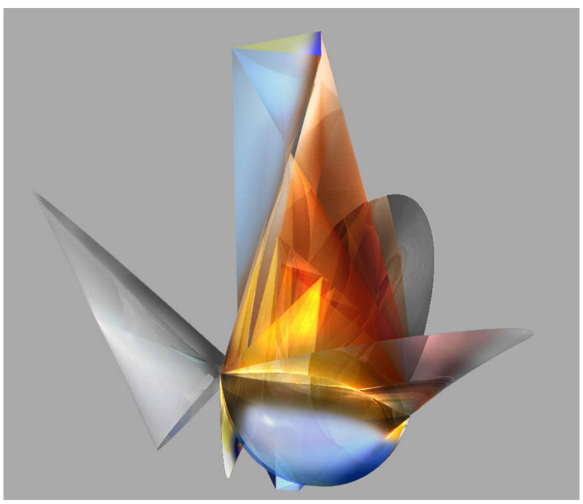


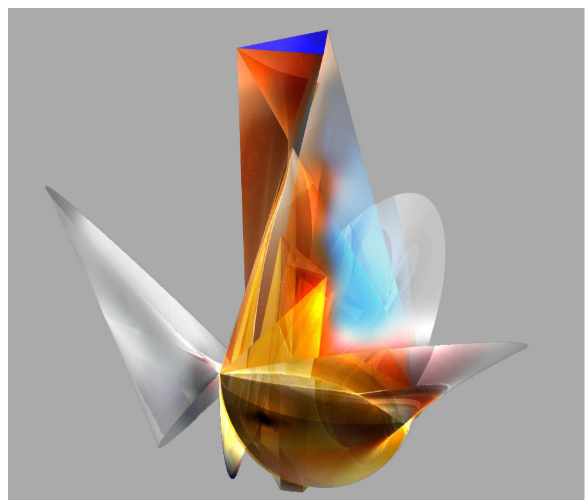


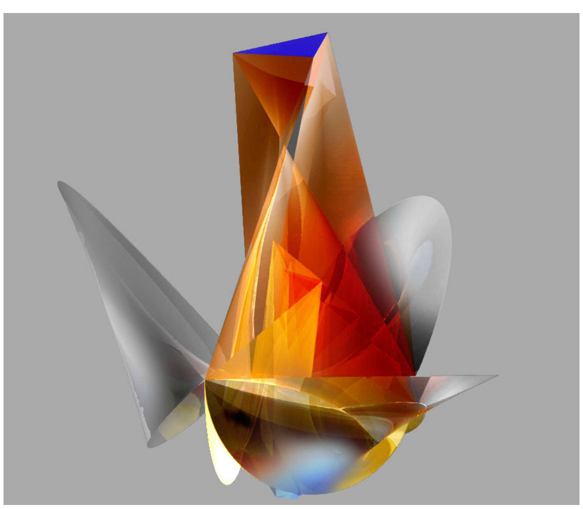
Appendix B: Supplementary Sketches

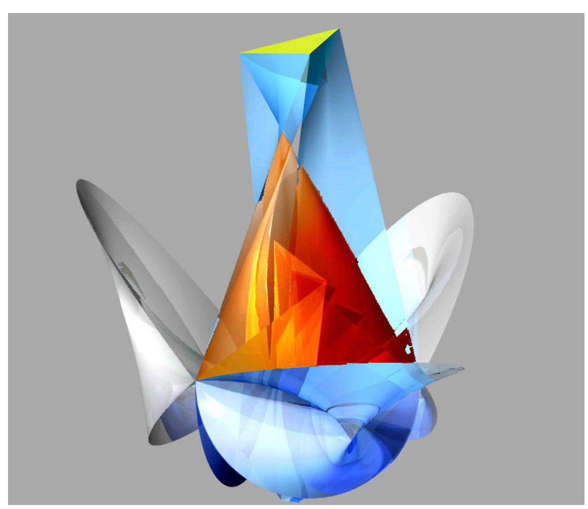


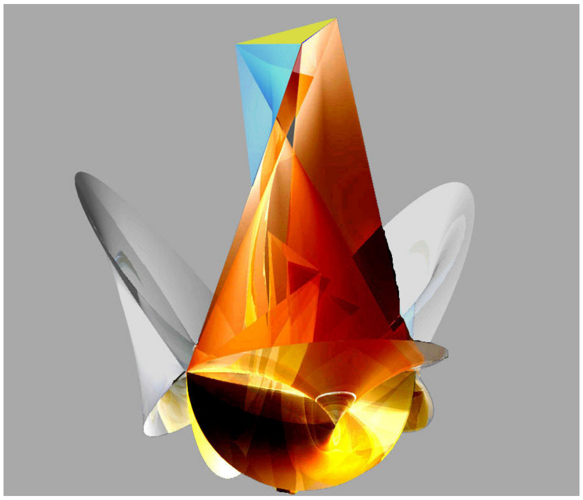


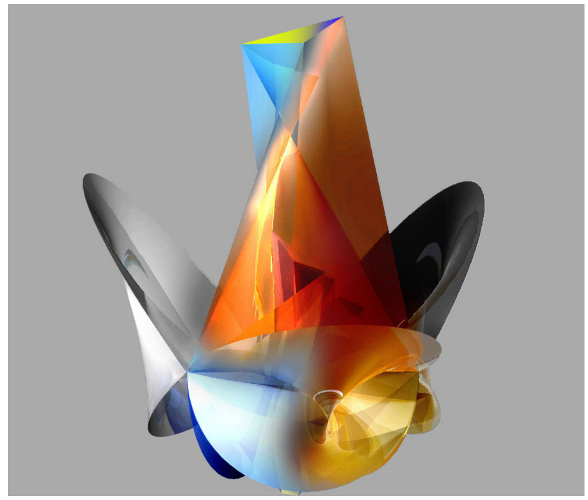


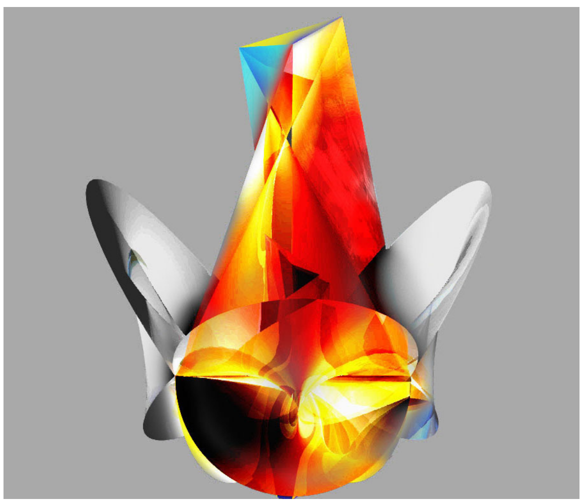


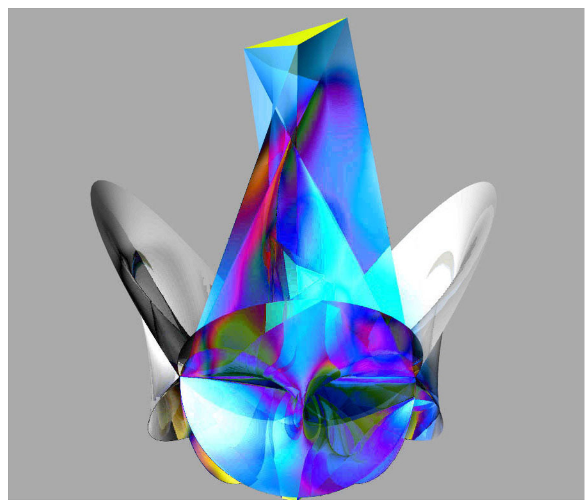












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