A Design Visualization Machine: An agile prototype for architectural plans on a finite grid

by Yu Linlin Huang

Submitted to the Department of Architecture and Planning in partial fulfillment of the requirements for the degree of

B.S. Architecture

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Abstract

This thesis project proposes a rapid visualization machine that can produce agile prototypes of simple architectural plans on a finite grid system. While various visualization systems to demonstrate instantaneous three dimensional form generations have been implemented recently by automobile industries and artists, a small scale visualization machine for architectural planning purposes has not been tested. Through careful analysis of the minimalist architectural plans of Ludwig Mies van der Rohe and research into the schematic plans of Palladian villas, it was determined that 1) fundamental structural components are the column and the wall, and 2) simple architectural plans can be well represented by a finite grid system on which those components are laid out. The proposed system is composed of repeatable, independent modular pieces; each houses one column unit and two wall units that can be extruded or restructured depending on the designs of the user. Those components are driven by servo motors which translate into agile movements to instantly reflect any change of layout a designer draws in the software. The current machine design with a 4 x 4 module grid can create a completely enclosed 3 x 3-grid plan and is able to visualize simple plans layouts. With the increased number of modules in the machine, a higher number of combinatorial plan schematics can be represented and more complex architectural plans can be visualized. The analysis of plans suggest a finite 12 x 12 module grid on the machine, or a 11 x 11-grid plan, is sufficient in the context of visualization for commonly practiced residential designs of architecture.

Thesis Supervisor: Takehiko Nagakura (Ph.D)

Title: Associate Professor of Design and Computation

"If you don't want to be forgotten
when you're dead and rotten
write something worth reading
or do something worth the writing."

-Ben Franklin

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My four years as an undergraduate student at MIT has culminated in this project, embodied in the pages of this book. It is a bittersweet feeling to arrive at this moment, the time to leave this new home. But it is comforting to think that even though I will leave MIT, MIT will never leave me because the experiences I have had and the friends I have made will stay with me forever.

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Chapter 1 : Introduction

Architects rely on 3-D modeling software to create, modify, optimize and visualize their designs digitally. During the design process, the ability to visualize the product in 3D is important for creating successful prototypes and for analyzing the feasibility of the design. Apart from using modeling software for digital visualization, designers can also realize design prototypes through the design fabrication process. The tools that allow one to create a physical prototype include laser cutters, water jet, CNC machines, and 3D printers. There are pros and cons to each of those methods in making the physical prototype and the choice of the tool depends largely on the design. In other words, for the designer who would benefit from a rapid visualization of a simple architectural plan, he must labor through a series of routine steps in the fabrication process to create the physical model. Once one model is created, any new modifications would require a new model, thus recreating the process to create another one. The task of modeling and remodeling simple structures often takes time and requires much patience to complete.

This thesis proposes a design visualization machine as an alternative technique for rapidly generating a prototype of simple architectural plans. A number of projects have been created which revolutionized the form-finding process and allow artists to explore the 3D space through digitally-controlled responsive environments. However, no existing machine allows architects to explore the ability to visualize simple plans on a finite grid system. This aim of this thesis is to analyze architectural plans and to design a machine that is able to represent them through a finite grid system.

1. Background

The ability to visualize design ideas in the physical world is critical not only to architects but to product designers and other artists who work with physical mediums. Tangible representations are used to communicate design ideas, and quickly constructed models or prototypes are efficient for a three dimensional understanding of the interaction of volumes and is a practical method for exploring ideas. These visualization methods come in a variety of forms and in a variety of technologies. This background section will augment the subject matter of the thesis through a discussion of notable precedents with elements from which the proposed thesis project can draw inspiration in the idea, design, actuation techniques, construction methods, and modes of operation.

The idea of moving modular pieces that is repeated in arrays to create a larger installation of moving pieces is not a new one. Kinetic structures are one type of movable structure that typically augment the movements of modular components by increasing the number of module elements. Examples of kinetic structures include anything from drawbridges to artistic installations. The common component in kinetic structures is the technology that actuates the individual modules. The BMW museum in Munich was home to a mechatronic art installation developed by ART+COM in 2008 which explored the form-finding process through 714 individually controlled metal spheres. Each sphere hangs from a steel wire and is controlled by its own stepper motor so that it has the ability to retract and lower independent of all the other pieces (Fermoso). The space in which the installation operated spanned an area of six square meters (Fermoso). The 714 independently moving metal spheres are analogous to the control points of a virtual model in a 3D modeling software. As designers who are accustomed to working in the 3D virtual model environment know, the more control points there are, the more precise the virtual model has the potential to be. Even though an unlimited number of control points is possible in a virtual world, there are certain production constraints that limit the number of "control points" in the physical world. The mechatronic installation at the BMW museum showcased the possibilities of form-finding through a process with limited precision, with limited numbers of "control points": a finite grid of control points is able to create artistic visualizations with many variations (Fermoso).

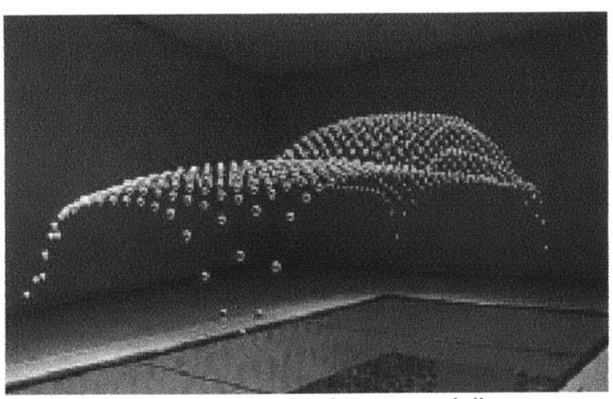

Image 1: BMW Kinetic Sculpture modeling a car.
[image source]: ART+COM. Kinetic Sculpture. BMW Museum, Munich. 2008.

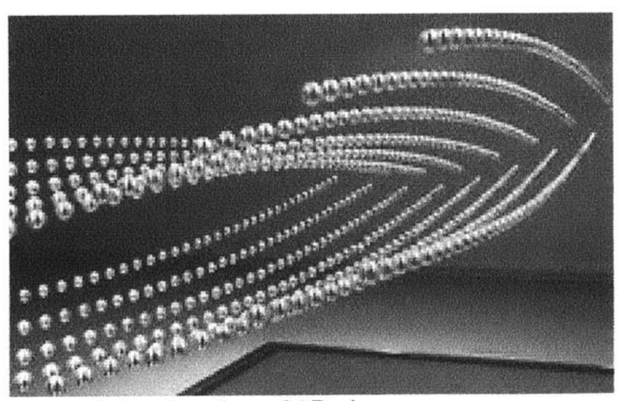

Image 2: Exploration of 3D shapes.
[image source]: ART+COM. Kinetic Sculpture. BMW Museum, Munich. 2008.

A similar kinetic sculpture project called Kinetic Rain (2012) is a new mechatronic installation at the Changi Airport in Singapore. Also created by ART+COM, this piece is made up of two parts that are symmetrical to the other framing a central escalator (Rosenfield). This structure is composed to 608 droplet shaped modules on each of the two parts, making it the largest public kinetic sculpture installation in the world with 1,216 individually controlled modules (Rosenfield). With this project, even though the total number of modules increased, each part of the installation has around 100 fewer modules with which to create the visualizations. Even though, a great number of visualizations –airplanes, organic shapes representing clouds, mountains, and ocean waves – is still achieved by this smaller module-grid system. The ability to understand the visualizations from the choreographed sequences of Kinetic Rain and the Kinetic Sculpture at the BMW museum shows the human eye's ability to interpret imprecise visual representations of concrete physical objects due to an ability to recognize patterns and common objects (Mitchell).

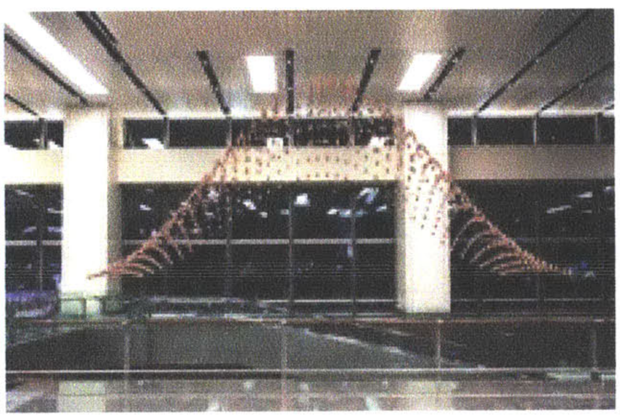

Image 3: Kinetic Rain structure modeling a parabola in the Changi Airport.
[image source]: ART+COM. Kinetic Rain. Changi, Singapore 2012.

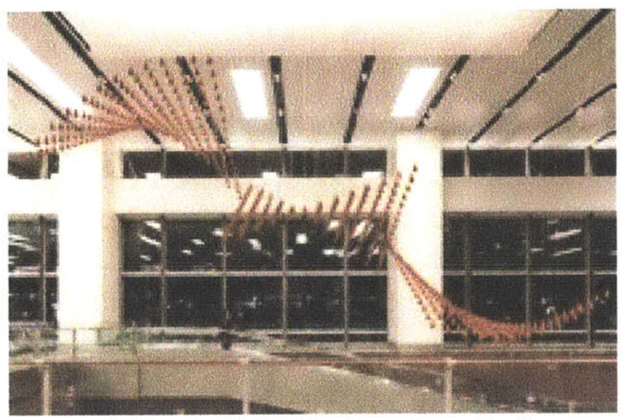

Image 4: Kinetic Rain structure form finding process in the Changi Airport.
[image source]: ART+COM. Kinetic Rain. Changi, Singapore 2012.

A joint project by ART+COM and light fixture manufacturer Selux recently produced Manta Rhei, a kinetic lighting fixture that is based on the organic light-emitting diode (OLED) technology. In a press release by Selux, the Manta Rhei "combines light scenes and movement patterns into a series of carefully designed individual choreographies. One such choreography brings to mind the gentle movements of the manta ray (Selux)." The fixture is composed to individual modules which allows the user freedom to freely scale the lighting fixture to suit any space (Selux). The original installation as described in the project descriptions on ART+COM consists of only fourteen 1.2-meter modules, each attached to hidden motors with steel wires. Just like the other mechatronic installations by ART+COM, each motor is individually controllable. With only 14 modules, the Manta Rhei is able to mimic the movements of a marine animal (ART+COM). Once again, a finite grid system of modular pieces provides wide opportunities for three dimensional visualization.

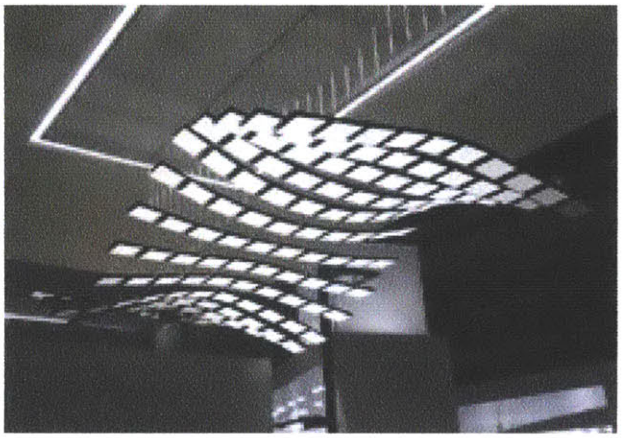

Image 5: Manta Rhei installation in the form finding process with a finite grid system.
[image source]: ART+COM. Manta Rhei. 2012.

Image 6: Manta Rhei imagined as a kinetic in-home lighting fixture.
[image source]: ART+COM. Manta Rhei. 2012.

Apart from the kinetic installations ART+COM has created, there are notable others as well. For the 2010 World Expo held in Shanghai, China, sixteen of the largest private corporations in China who financed the event reached out to Fisher Technical Services (FTSI) to realize a large kinetic sculpture. After three months the project – a 6m x 18m grid array of 1,008 spheres each controlled by its own motor – is completed (Fleming). Each of the spheres is capable of moving at high speeds up to 3 meters per second (Fleming). The speed and size of the grid allows rapid visualization of virtually infinite shapes and movements (Fleming). The interesting part of this particular project which sets it apart from the kinetic installations ART+COM created is that FTSI created a user-facing interface component that allows a creative team with no programming experience unlimited freedom to experiment with form and dynamic animation possibilities in a live setting (Fleming). The FTSI engineers programmed the movement of each module, or sphere, using video files (Fleming). For this process, a 1,008-pixel video frame was created, each module corresponding to a specific pixel (Fleming). The height value of each module corresponds to the gradient value of the pixel: white would lower the spherical module to the lowest point, and black would completely recoil the module back to the ceiling (Fleming). The speed of the module is controlled by the speed of transition from one gray scale value to the next. In addition to the user-facing interface, an admin-facing interface allows back-end programmers to pre-visualize the desired effects in simulation before the kinetic installation reveals it to the public (Fleming).

A different type of kinetic mechatronic art that does not involve spherical balls to generate three dimensional visualizations through vertical movement is two dimensional rapid visualization system which relies on horizontal movements. One such project is Wooden Mirror created by Daniel Rozin in 1999. Rozin created four mechanical "mirrors" made out of various materials (Rozin). The scenario is whenever a person approaches one of the mirrors, an image of the person is instantly reflected on its surface (Rozin). Each "mirror" is composed of 830 square pieces of wood, 830 servo motors, and a camera; each module component is controlled individually and responds to reflect the computer analysis of the recorded camera image (Rozin). In his own words, Rozin explains, "This piece explores the line between digital and physical, using a warm and natural material such as wood to portray the abstract notion of digital pixels (Rozin)." From the images of this project (image 7 and image 8), the size of the real object is multiplied when reflected in the "mirror." This scaling process coupled with large grid size undoubtedly allows the mechanism to be highly precise. From the previous examples of kinetic sculptures, it is strongly suggested that the eye is able to identify certain patterns even if a representation is imprecise. Therefore, the interesting question regarding this project is what type of image can the artist achieve with a grid size half as large, or a fourth as large? What is the lowest resolution grid that can be used to still reflect a recognizable visualization?

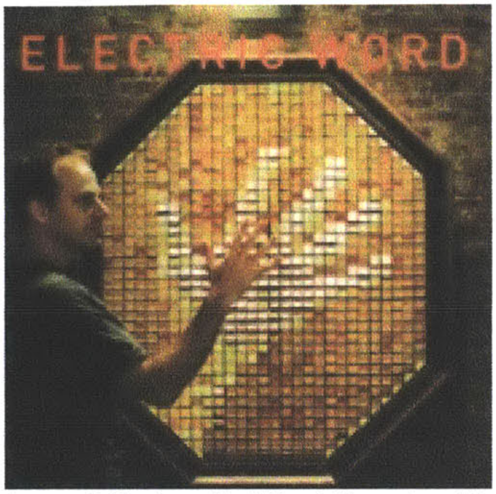

Image 7: Featured in Wired Magazine, Wooden Mirror describes a hand with a finite grid.
[image source]: Daniel Rozin. "Mechanical Mirrors." Daniel Rozin Interactive Art. 1999. url: http://www.smoothware.com/danny/woodenmirror.html.

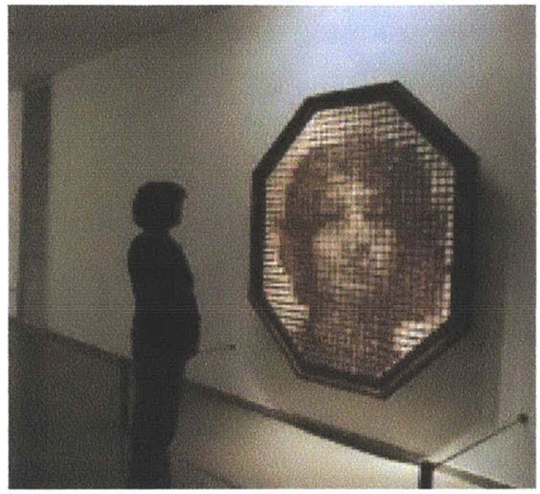

Image 8: The woman's face can be represented by this finite grid. The resolution of the image will increase as the size of the grid increases.
[image source]: Daniel Rozin. "Mechanical Mirrors." Daniel Rozin Interactive Art. 1999. url: http://www.smoothware.com/danny/woodenmirror.html.

To address the issue of resolution it is necessary to discuss a kinetic light sculpture aptly named f5x5x5 by LAb[au], a Belgian interactive design studio. This sculpture is designed to be a low resolution display that can be programmed (Murph). The framework is extremely small containing only twenty five modules arranged in a 5x5 grid system. The front size of each module is white, which the back is black; this allows the work to be programmed in binary. Each module is controlled by two stepper motors to support bi-axial rotation for the frames (Murph). When the project was installed in le Basilique de Saint Denis in Paris, the single framework is repeated five times, resulting in a 125 pixel screen. According to Engadget, "the installation is a part of a larger "16n" project designed to confront architectural projects (such as congestion and flows) with spatial sensing technologies (Murph)." The f5x5x5 essentially functions like a huge bitmap, able to visualize pixelated images at this resolution, creating images much like a QR code or a RF code. While the visualizations of the smaller-grid, low resolution system is certainly not as robust as much larger grids, there are still many opportunities for the system as a visualization machine – it can visualize numbers and letters.

A project sponsored by the Hyundai Motor Group uses square modules in a large grid system, the size of a gymnasium, to immerse the audience in the three-sided display. The Hyper-Matrix is a kinetic landscape installation in 2012 by Jonpasang. Each modular component is a 320mm x 320mm Styrofoam cube which are mounted into their own actuators, moved back and forth by stepper motors (Wells). The making of the Hyper-Matrix is an extremely complex task. The construction process for the Hyper-Matrix lasted two months, in which huge steel cubicles were constructed to support the thousands of electrical components required to control the movement of the modules (Wells). The resulting structure stretches 45 meters wide and 8 meters high. In the end, the resolution and size of the system is able to display an infinite number of forms on the moving, vertical walls (Wells). Audiences experience these walls as a moving screen displaying projected images.

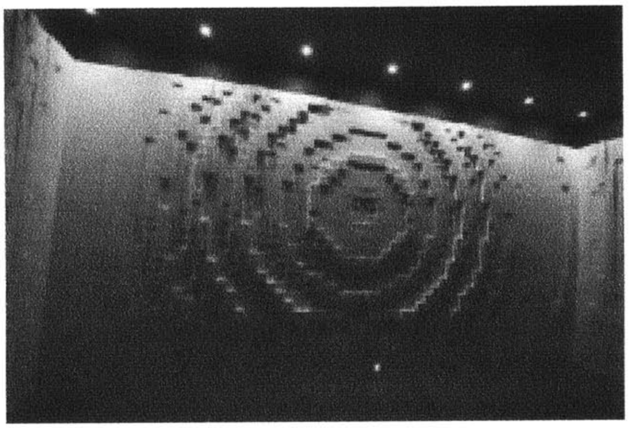

Image 9: The hyper-matrix representing the effects of a water droplet at the 2012 Yeosu Expo.
[image source]: Jonpasang. Hyper-Matrix. Hyundai Motor Group Pavilion, Yeosu Expo, 2012.

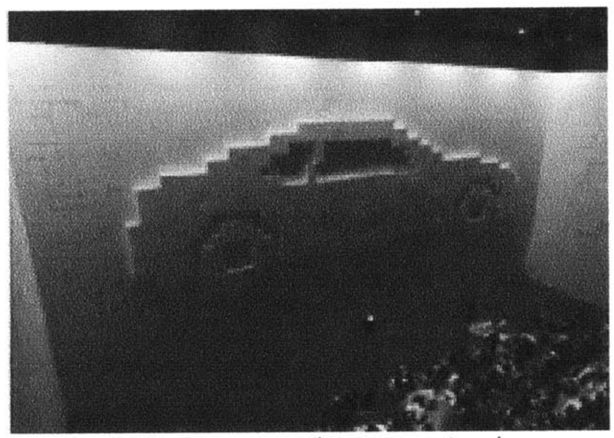

Image 10: The hyper-matrix represents a low-resolution car with a finite grid at the 2012 Yeosu Expo.
[image source]: Jonpasang. Hyper-Matrix. Hyundai Motor Group Pavilion, Yeosu Expo, 2012.

All of the precedents mentioned up until now uses the servo as the main mechanism to actuate the moving modules. A project from the MIT Media Lab's Tangible Media Group called Recompose proposes a new system to manipulate an actuated surface. The students who worked on the project realized the shortcomings of direct manipulations to change the shape of a physical object. Instead, they proposed a new system which accepts a mix of gestural and direct manipulations to modify the shape of a modular grid system, with an array of 120 movable modules (Leithinger and Lakatos). The part of the Recompose most interesting to this thesis is the way in which each module of the grid system is actuated. Instead of using motors to move each square piece up and down, each module is actuated with ALPS motorized slide potentiometers, a sliding potentiometer used in audio mixing boards (Leithinger and DeVincenzi). This actuating system allows the modules to be controlled in 1 mm increments (Leithinger and Lakatos). However, the spacing between each module is limited by the size of the sliders. As such, the final prototype arranges the modules in a square grid with 5cm spacing (Leithinger and Lakatos).

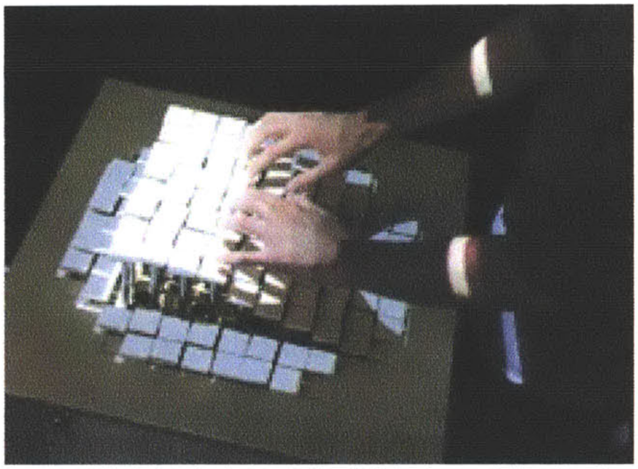

Image 11: The height of individual modules in Recompose can be controlled by the hand motions. [image source]: Tangible Media Group, MIT Media Lab. Recompose. 2011.

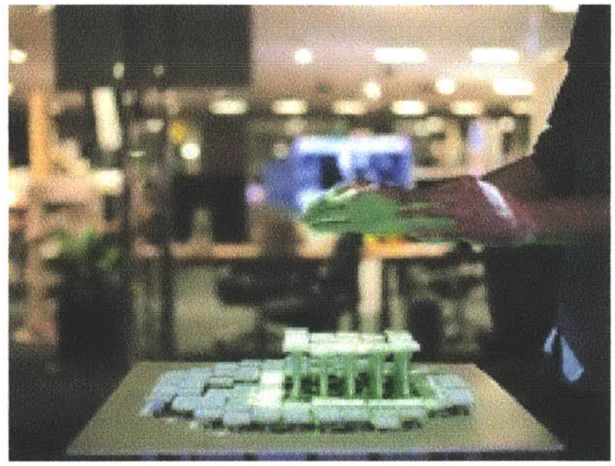

Image 12: The actuated area within Recompose is controlled by the area over which the hand hovers. [image source]: Tangible Media Group, MIT Media Lab. Recompose. 2011.

An altogether different type of method to actuate extrusions on a surface is using microfluidic actuators. Tartus Technology recently premiered a novel physical keyboard for touch-screen devices that uses microfluidic actuators (Das). Behaving much like ink-jet fluids, the microfluidic actuators are able to provide haptic feedback, enabling users to type more quickly and accurately, and allowing sight-impaired users to communicate through typing (McCallum et al). The microfluidic system allows the physical keys to "bubble up" from the surface of the touch screen when needed, and retract to make the screen smooth again when finished typing (Das). The mechanics function in this way: the screen of the device has a sub-panel permeated with channels which become filled with fluid when pressure is increased (McCallum et al). When this channel is filled, it becomes extruded on the device surface to create a physical key (McCallum et al). This actuating system does not require a mechanical device as it is fully fluid-based (McCallum). However, as this type of actuating system is so new, it is likely not see commercial market in the near future (Das).

Bringing the discussion back to projects that explore the form-finding process, a project created by Elsie Elsacker and Yannick Bontinckx from the University college of Science and Art, Sint-Lucas Brussels, Belgium, developed a kinetic pavilion that responds to changes in weather and the flow of people (Elsacker). This project explores a dynamic fluid shape-forming process through the control points (Elsacker). The kinetic model of the pavilion aims to redefine the three dimensional space by responding to digital data inputs taken from the environment surrounding it. The pavilion is created with 28 critical points; each point is linearly actuated by a rack and pinion system controlled by a servo motor through a computer (Elsacker).

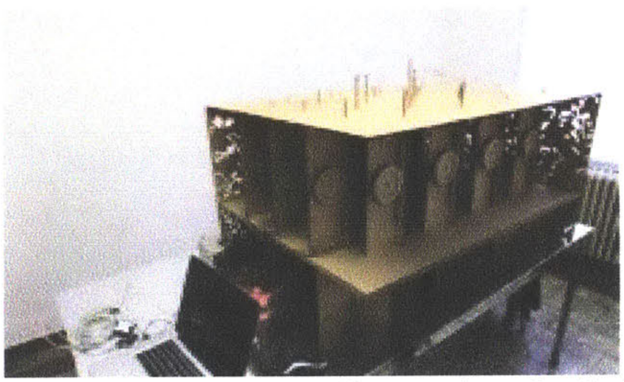

Image 13: The kinetic pavilion consists of critical points that are linearly actuated by a rack and pinion system. The movement of these points create the dynamic movement in the pavilion.
[image source]: E. Elsacker and Y. Bontinckx. Kinetic Pavilion 1.0. 2011. url: http://eliseelsacker.wordpress.com/2011/04/20/update-finale-kinetic-pavilion/.

Image 14: The orientation of each triangle shape is determined by the height of each control point.
[image source]: E. Elsacker and Y. Bontinckx. Kinetic Pavilion 1.0. 2011.url: http://eliseelsacker.wordpress.com/2011/04/20/update-finale-kinetic-pavilion/.

2. Project Contribution

This thesis proposes a design visualization machine, an agile prototype for architectural plans on a finite grid. It has a virtual and physical component: the designer interacts with the user interface to create a simple architectural plan, and the physical device reflects the user input. The machine creates a physical representation of an architectural plan on a finite grid system, and the resolution of the plan is determined by the grid size – increasing the amount of modules increases the resolution of the plan. It provides a simple way for architects to visualize their designs with design flexibility and fast visual feedback.

3. Thesis Organization

This thesis is organized into five chapters. Chapter 1 presented the project idea as well as a series of related projects to provide background for understanding the purpose and the contribution of this thesis project. Chapter 2 presents an analysis of floor plans by Mies Van der Rohe, Palladio, and current apartment plans. Chapter 3 will detail the design and fabrication of the hardware. Chapter 4 explains the software portion of the machine; it explains how the user interacts with the machine and the functionalities supported by it. Chapter 5 discusses the successes and failures of the design of the machine and makes suggestions to improve the machine for future explorations.

Chapter 2 : An Analysis of Architectural Plans

Beautiful architecture is geometrically simple and whose spatial atmosphere is easily understood. Minimalistic logic in architecture tends to eliminate superfluous ornamentation and reduce designs down to the most essential elements in order to achieve simplicity. In classical temple architecture of Ancient Greece and Rome, the composition of columns and walls follow very specific grammatical rules (Mitchell). In his writings about the theory of architecture, Vitruvious points to symmetry and proportion as the fundamental grammar of temple architecture: "No temple can be put together coherently without symmetry and proportion (Vitruvious)." Similarly, minimalist architecture follows a certain set of rules with an emphasis on simplicity in the composition of forms. Marked symmetry and attention to minimization of extraneous detail can be found in the floor plans of villas by Palladio in the 1500s as well as in the more recent, post-twentieth century works. Much like Palladian architecture, Modernist architecture, marked by the simplicity of form and the emphasis on horizontal and vertical lines, can also be categorized as minimalist architecture. Well known architects in the modernist architectural movement includes prominent figures such as Le Corbusier, Ludwig Mies van der Rohe, Alvar Aalto, Frank Lloyd Wright, and Peter Zumthor. The motto adopted by Mies van der Rohe "less is more" is the most concise yet clear testament of minimalist ideals.

An important component of this thesis project is to analyze the structural components in architectural plans of minimalist architecture in order to develop a grid with rules to represent the plans with a minimum amount of components in a robotic visualization system. The goal is to determine the lowest resolution needed for the device to articulate multiple combinations of a set of selected plans. To perform this evaluation, it is necessary to examine the works of several different architects and multiple plans. For the purpose of analysis, the author has chosen to perform in depth examinations of Mies Van der Rohe's Dexel House, Lessing House, and Farnsworth House. Analysis of Palladio's villas as performed by Mitchell in his book The Logic of Architecture reveals similar characteristics in their grid-like formation. Finally, the fundamental components and the grammar of current residential complexes will be presented to verify that the proposed tool is applicable toward practical purposes.

1. Lessing House by Mies Van Der Rohe

1.1 Fine Resolution - Small Grid

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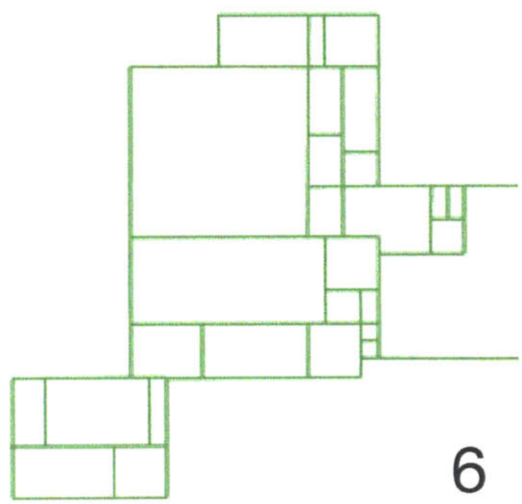
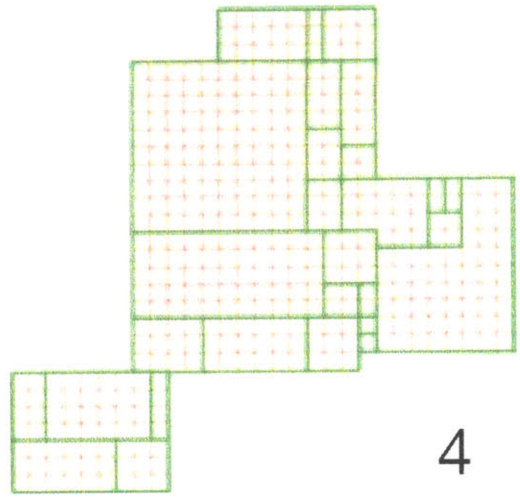


6

Image 15 : 1-6 "Lessing House"
[image source]: Wolf Tegethoff. "Mies Van der Rohe: The Villas and Country Houses." Richard Bacht Publishing. Essen, Germany. 1981.

3



4

1 This image is the original plan of Lessing House as designed by Mies Van der Rohe. Starting from the undimensioned layout, the author has arbitrarily chosen to use the square dimension of the smallest room in the plan as the basis of the small grid.

2 The red grid overlays the original plan. At the finest resolution, the Lessing House is represented by a 29 x 28 grid.

3 The green lines represent the approximations to the original plan based on the small grid. It overlays the grid and the original plan.

4 The green lines representing the approximation of the original plan overlays the small grid.

5 The green lines representing the approximation of the original plan overlays the original architectural plan. It shows the accuracy of the approximated representation using the 29 x 28 grid.

6 The new plan representing the original as an approximation using a 29 x 28 grid.

1.2 Medium Resolution - Medium Grid

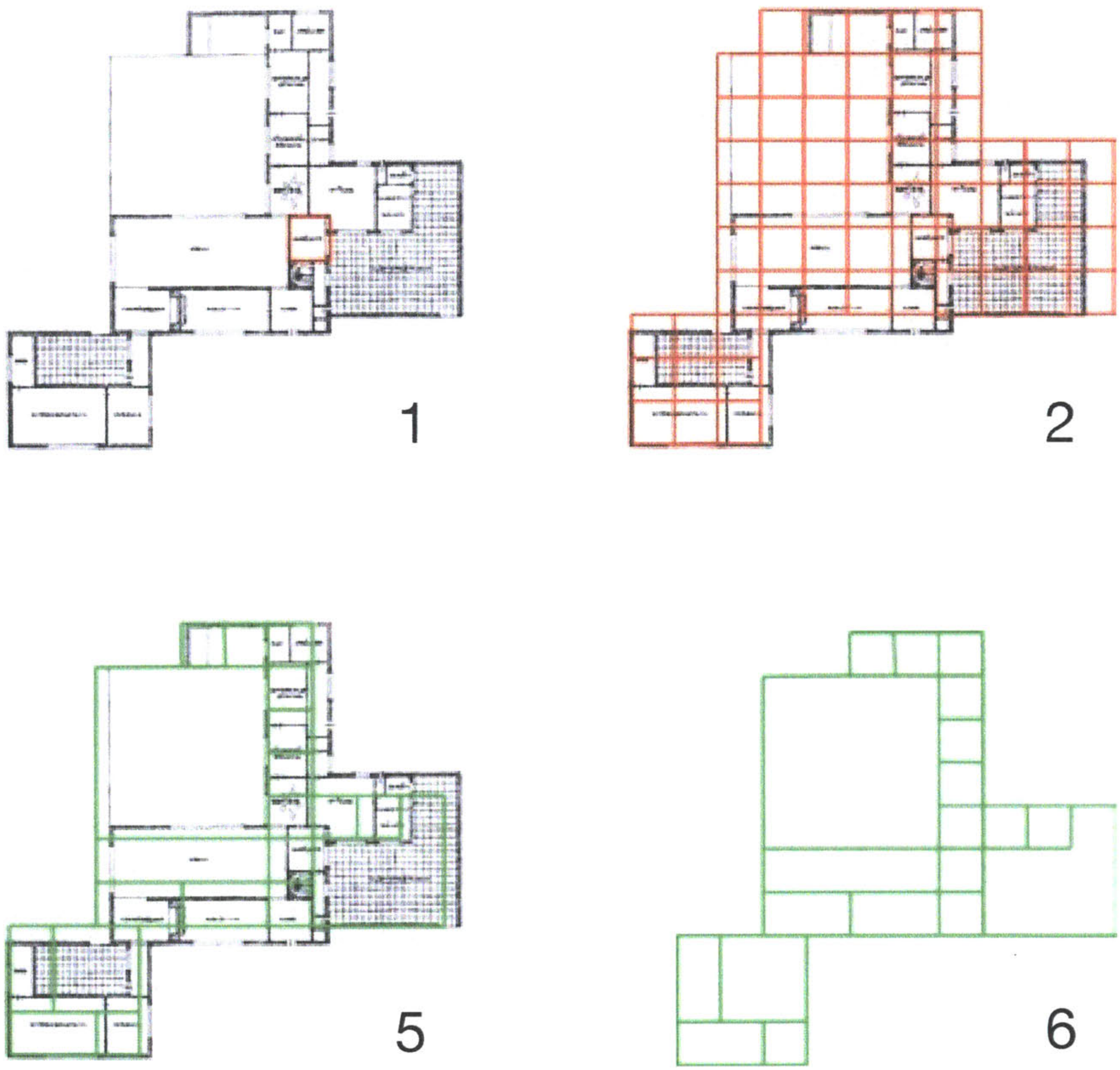


Image 16 : 1-6 “Lessing House”
[image source]: Wolf Tegethoff. “Mies Van der Rohe: The Villas and Country Houses.” Richard Bacht Publishing. Essen, Germany. 1981.

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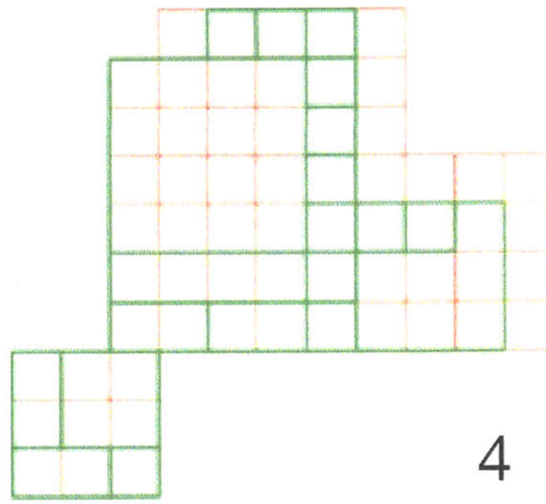


4

1 This image is the original plan of Lessing House as designed by Mies Van der Rohe. Starting from the undimensioned layout as in the small grid, the author has chosen a module approximately four times the size of the module of the small grid.

2 The red grid overlays the original plan. At the medium resolution, the Lessing House is represented by a 11 x 10 grid.

3 The green lines represent the approximations to the original plan based on the medium grid. It overlays the grid and the original plan.

4 The green lines representing the approximation of the original plan overlays the medium grid.

5 The green lines representing the approximation of the original plan overlays the original architectural plan. It shows the accuracy of the approximated representation using the 11 x 10 grid.

6 The new plan representing the original as an approximation using a 11 x 10 grid.

1.3 Crude Resolution - Large Grid

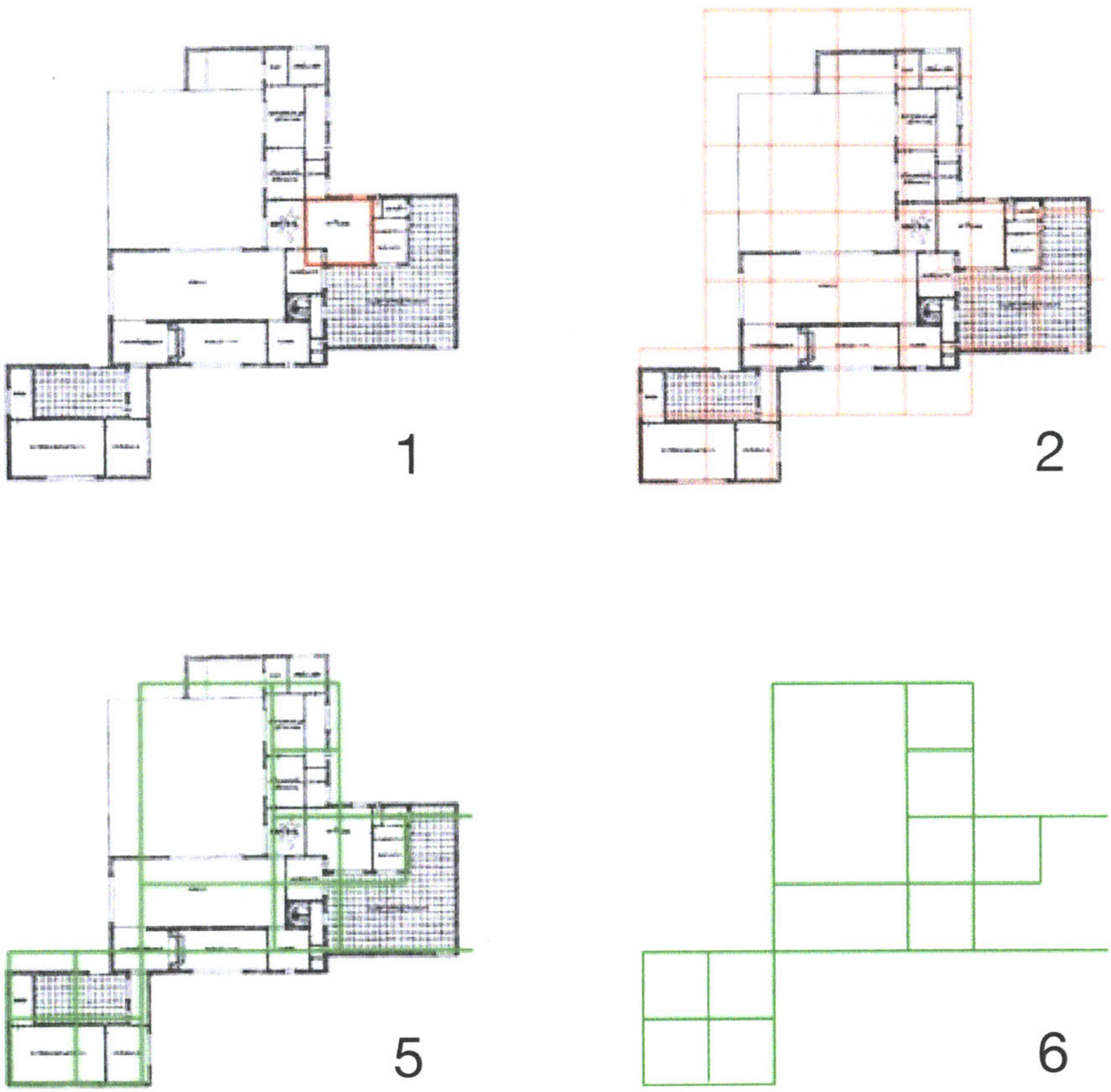
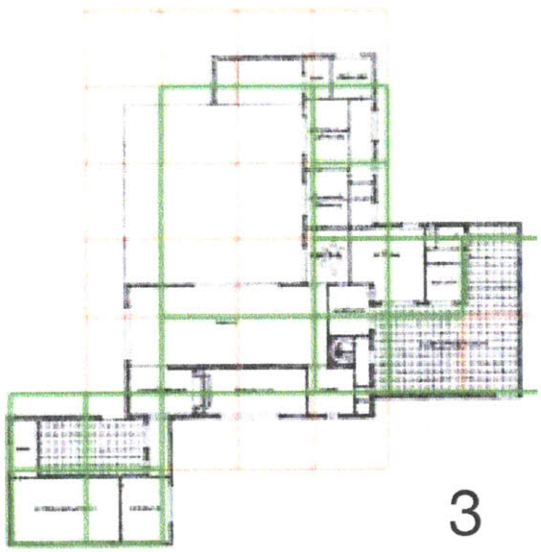


Image 17 : 1-6 “Lessing House”
[image source]: Wolf Tegethoff. “Mies Van der Rohe: The Villas and Country Houses.” Richard Bacht Publishing. Essen, Germany. 1981.



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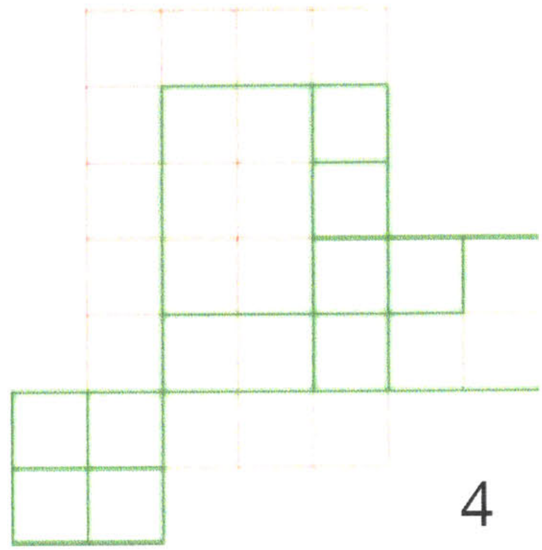


4

1 This image is the original plan of Lessing House as designed by Mies Van der Rohe. The author has chosen a module four times the size of the module of the medium grid, to be the modular unit of the large grid.

2 The red grid is overlays the original plan. At the crude resolution, the Lessing House is represented by a 7 x 7 grid.

3 The green lines represent the approximations to the original plan based on the large grid. It overlays the grid and the original plan.

4 The green lines representing the approximation of the original plan overlays the large grid.

5 The green lines representing the approximation of the original plan overlays the original architectural plan. It shows the accuracy of the approximated representation using the 7 x 7 grid.

6 The new plan representing the original as an approximation using a 7 x 7 grid.

2. Farnsworth House by Mies Van Der Rohe

2.1 Fine Resolution - Small Grid

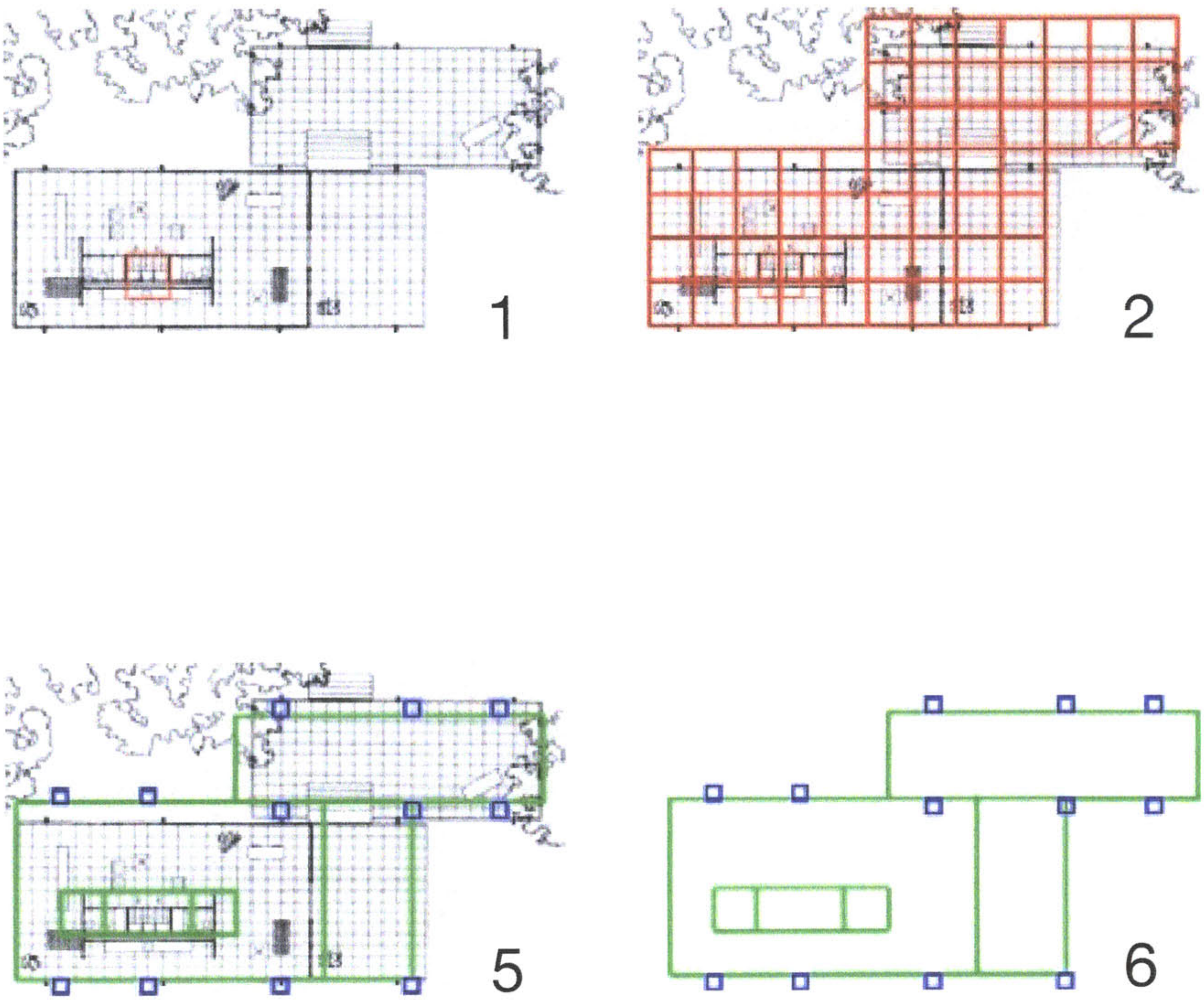
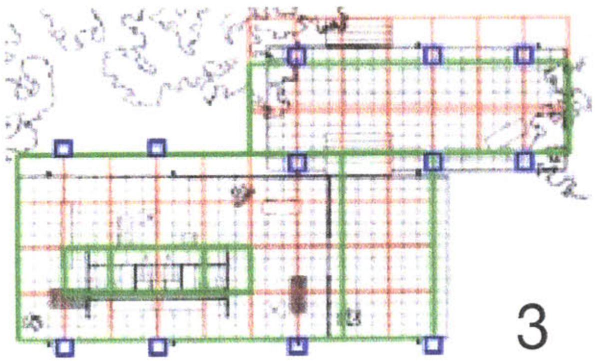


Image 18 : 1-6 “Lessing House”
[image source]: Wolf Tegethoff. “Mies Van der Rohe: The Villas and Country Houses.” Richard Bacht Publishing. Essen, Germany. 1981.



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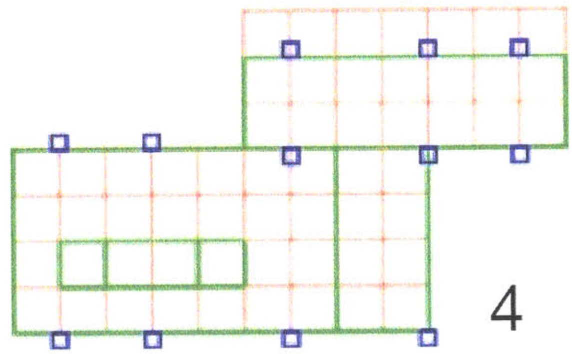


4

1 This image is the original plan of Farnsworth House as designed by Mies Van der Rohe. The original plan has already been dimensioned by a 28 x 25 grid. Since the 28 x 25 grid represents the original plan perfectly, the author has arbitrarily chosen a module that is 3 times larger in length and width as the module on the original grid.

2 The red grid overlays the original plan. At the finest resolution, the Farnsworth House is represented by a 12 x 7 grid.

3 The green lines represent the approximations to the original plan based on the small grid. It overlays the grid and the original plan. The blue squares represent the approximations of the columns on the corners of the module pieces.

4 The green and blue lines representing the approximation of the original plan overlays the small grid.

5 The green and blue lines representing the approximation of the original plan overlays the original architectural plan. It shows the accuracy of the approximated representation using the 12 x 7 grid.

6 The new plan representing the original as an approximation using a 12 x 7 grid.

2.2 Medium Resolution - Medium Grid

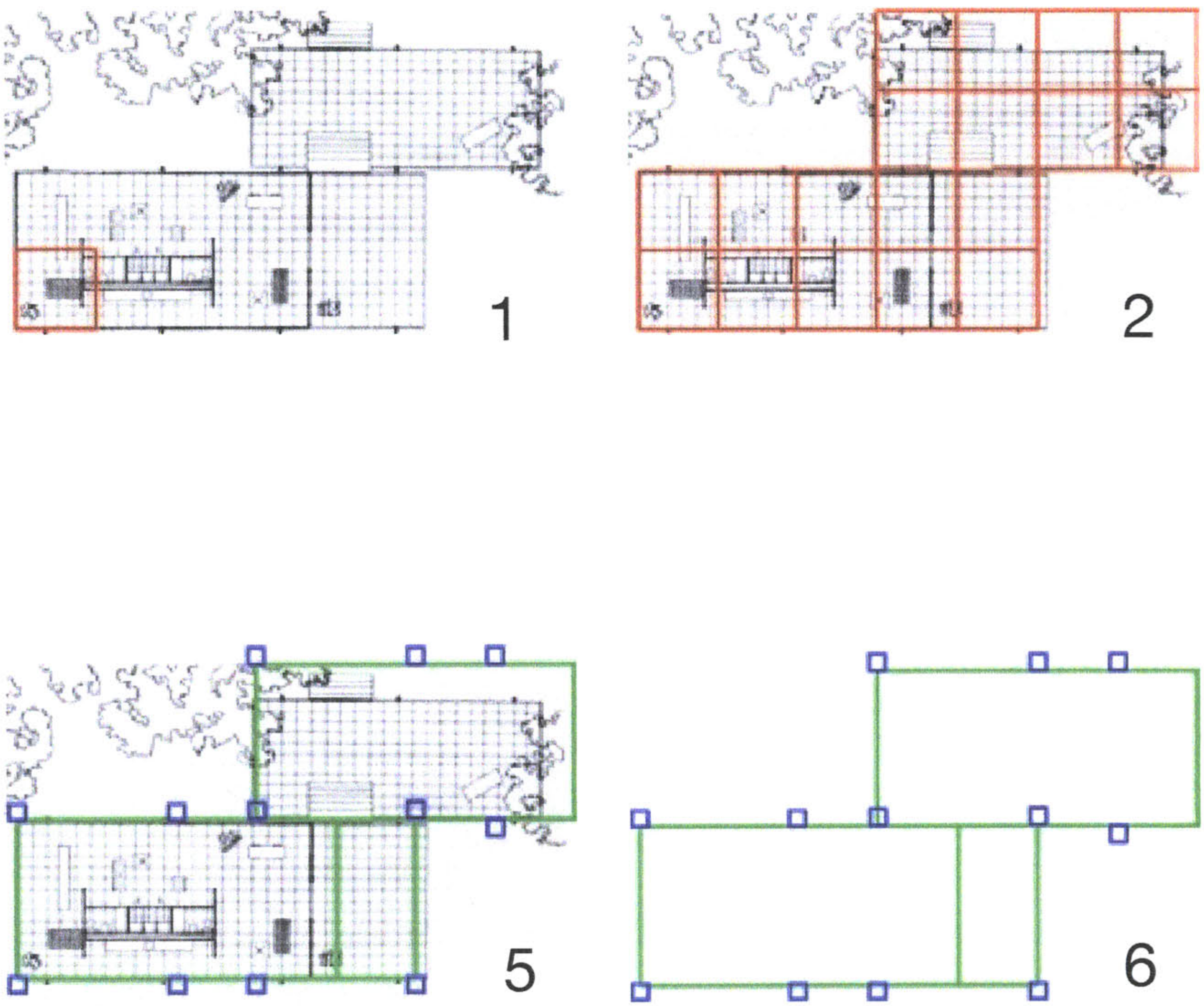
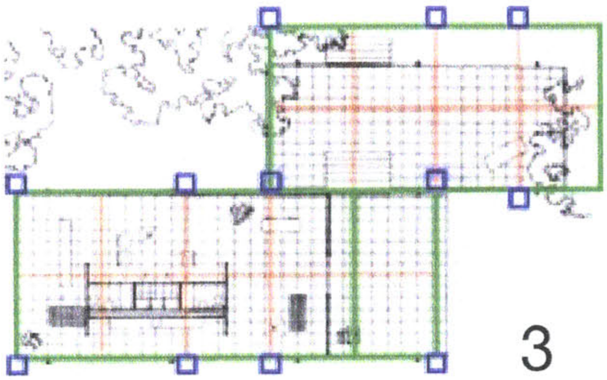
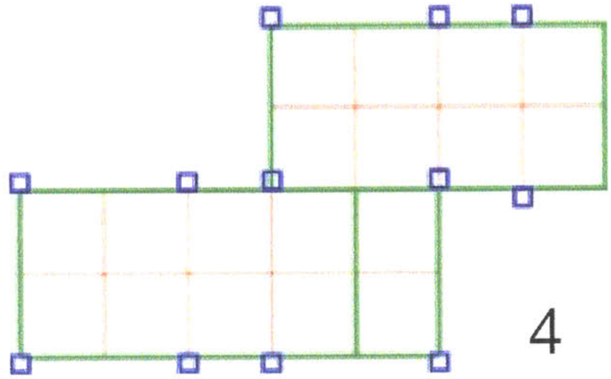


Image 18 : 1-6 “Lessing House”
[image source]: Wolf Tegethoff. “Mies Van der Rohe: The Villas and Country Houses.” Richard Bacht Publishing. Essen, Germany. 1981.



3



4

1 This image is the original plan of Farnsworth House as designed by Mies Van der Rohe. The module component of the medium grid is four times the area of the small grid's module.

2 The red grid overlays the original plan. At the medium resolution, the Farnsworth House is represented by a 7 x 4 grid.

3 The green lines represent the approximations to the original plan based on the medium grid, and the blue square represent the approximations to the columns in the original plan.

4 The green and blue lines representing the approximation of the original plan overlays the medium grid.

5 The green and blue lines representing the approximation of the original plan overlays the original architectural plan. It shows the accuracy of the approximated representation using the 7 x 4 grid.

6 The new plan representing the original as an approximation using a 7 x 4 grid.

2.3 Crude Resolution - Large Grid

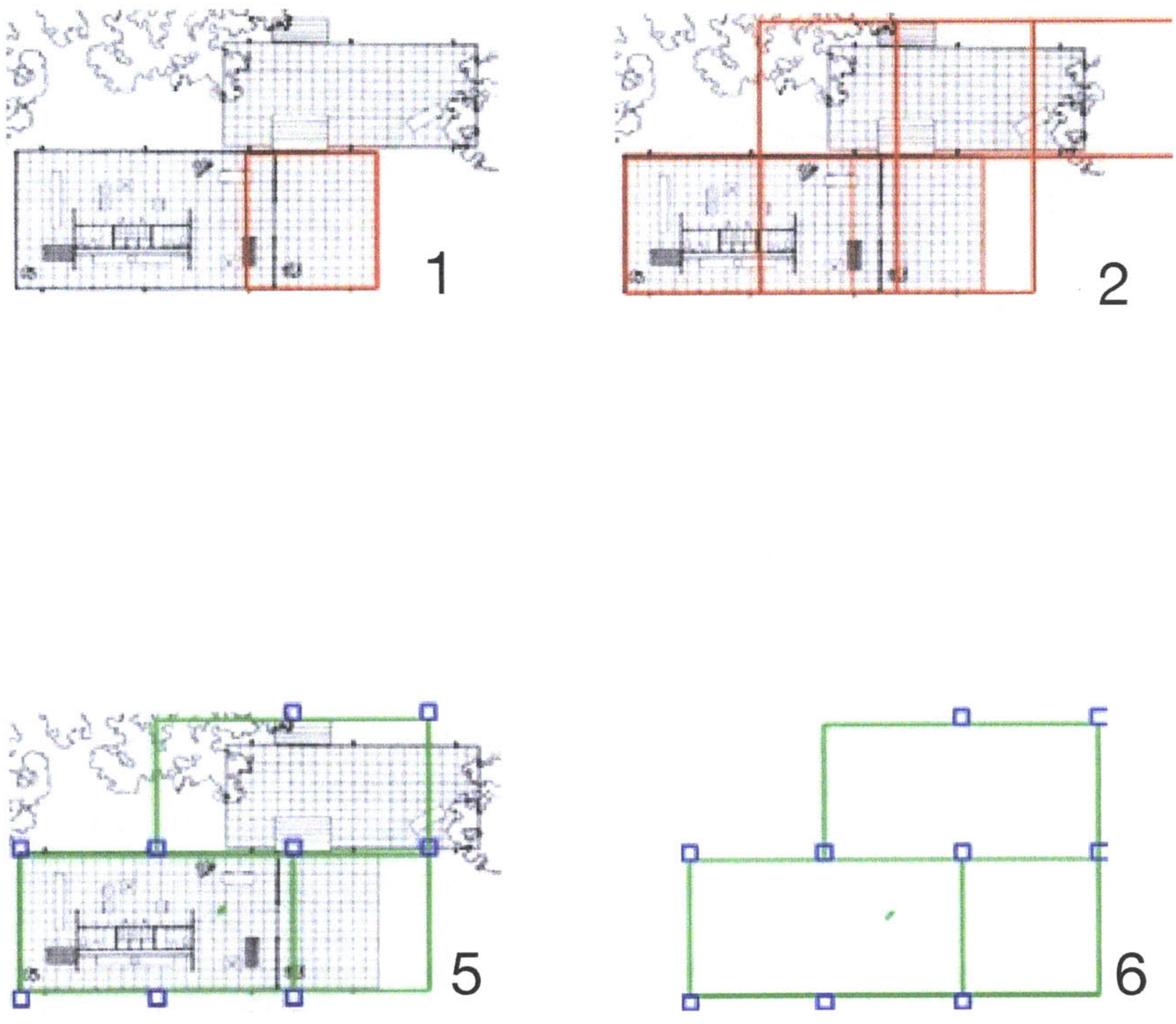
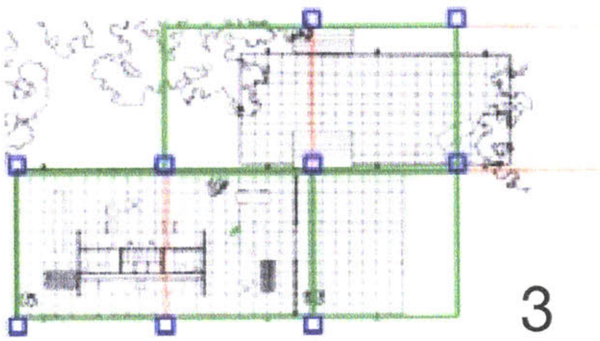
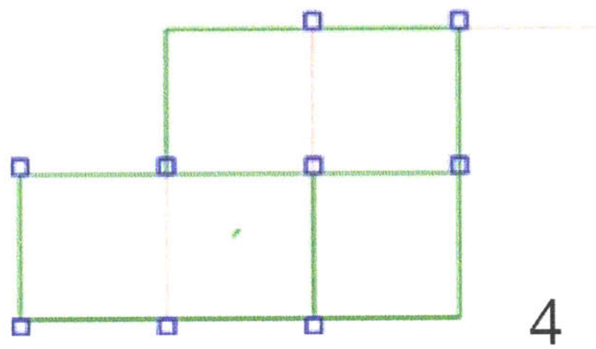


Image 19 : 1-6 "Lessing House"
[image source]: Wolf Tegethoff. "Mies Van der Rohe: The Villas and Country Houses." Richard Bacht Publishing. Essen, Germany. 1981.



3



4

1 This image is the original plan of Farnsworth House as designed by Mies Van der Rohe. The module component of the large grid is four times the area of the medium grid's module.

2 The red grid overlays the original plan. At the crude resolution, the Farnsworth House is represented by a 3 x 2 grid.

3 The green lines represent the approximations to the original plan based on the large grid, and the blue square represent the approximations to the columns in the original plan.

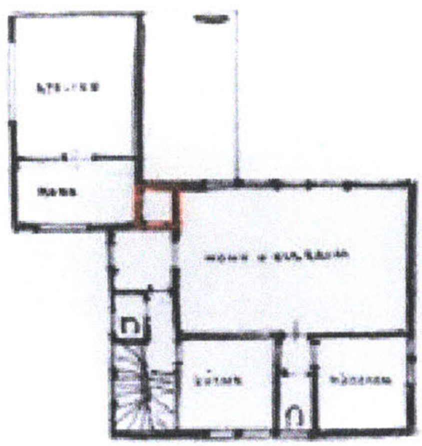
4 The green and blue lines representing the approximation of the original plan overlays the large grid.

5 The green and blue lines representing the approximation of the original plan overlays the original architectural plan. It shows the accuracy of the approximated representation using the 3 x 2 grid.

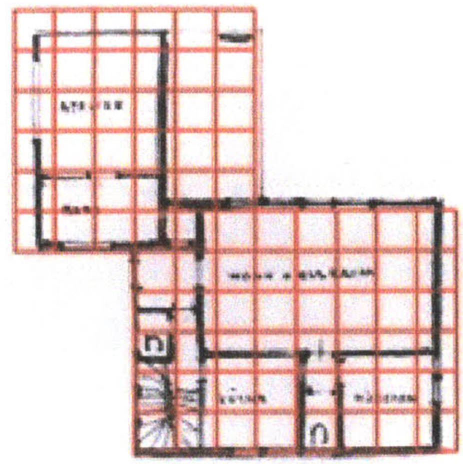
6 The new plan representing the original as an approximation using a 3 x 2v grid.

3. Dexel House by Mies Van Der Rohe

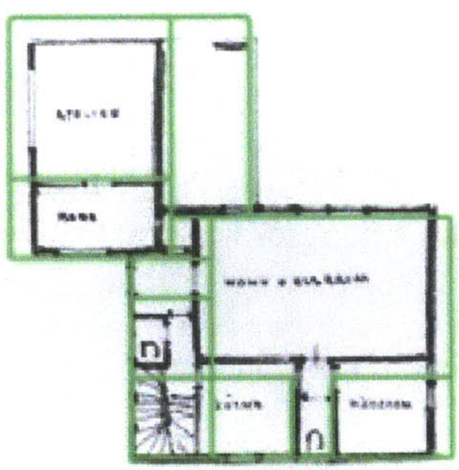
3.1 Fine Resolution - Small Grid



1



2



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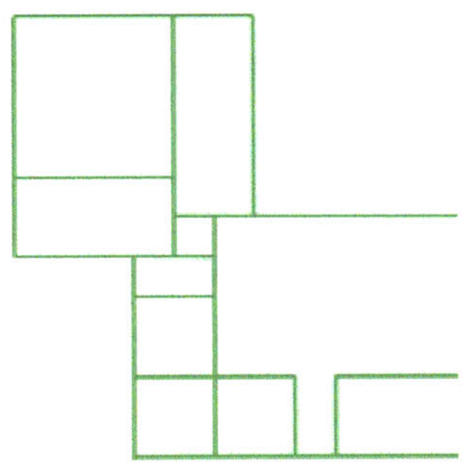
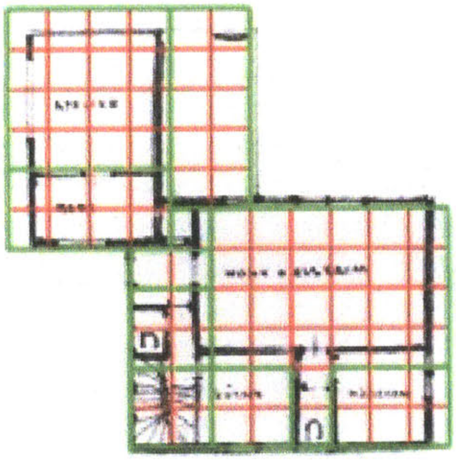


6

Image 20 : 1-6 "Lessing House"
[image source]: Wolf Tegethoff. "Mies Van der Rohe: The Villas and Country Houses." Richard Bacht Publishing. Essen, Germany. 1981.



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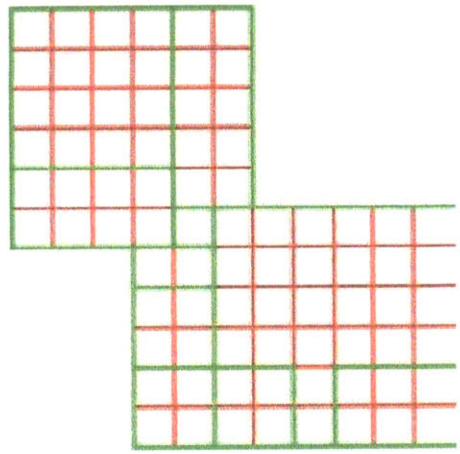


4

1 This image is the original plan of Dexel House as designed by Mies Van der Rohe. Starting from the undimensioned layout, the author has arbitrarily chosen to use the square dimension of the smallest room in the plan as the base module of the 11 x 11 small grid.

2 The red grid overlays the original plan. At the finest resolution, the Dexel House is represented by a 11 x 11 grid.

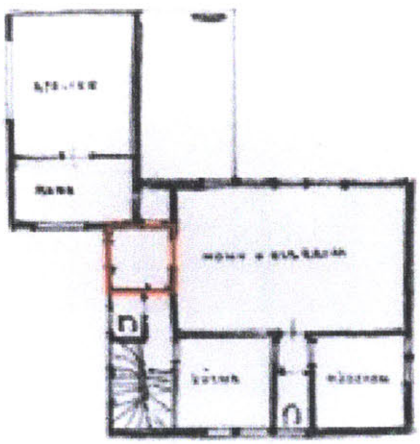
3 The green lines represent the approximations to the original plan based on the small grid. It overlays the grid and the original plan.

4 The green lines representing the approximation of the original plan overlays the small grid.

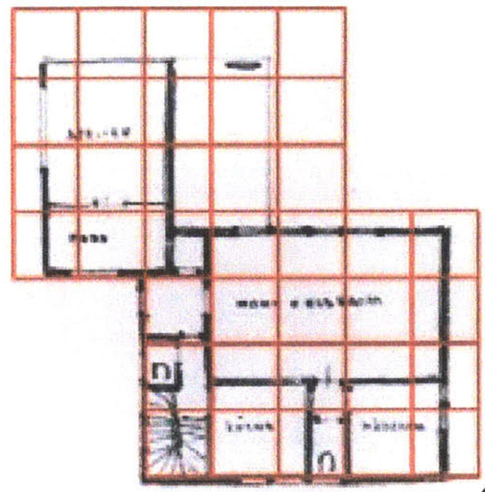
5 The green lines representing the approximation of the original plan overlays the original architectural plan. It shows the accuracy of the approximated representation using the 11 x 11 grid.

6 The new plan representing the original as an approximation using a 11 x 11 grid.

3.2 Medium Resolution - Medium Grid



1



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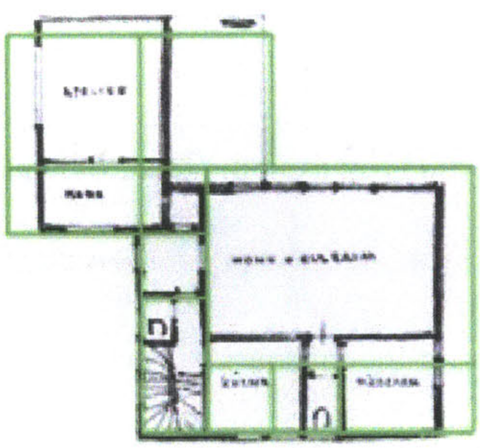

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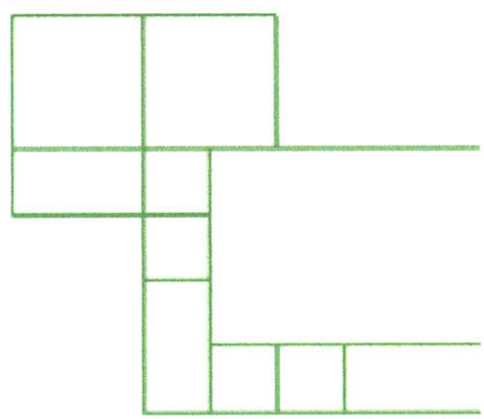
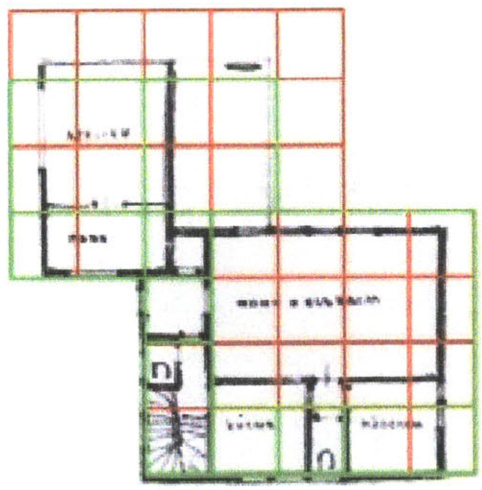
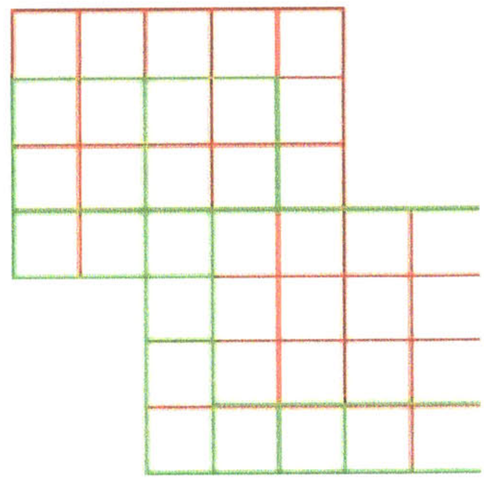


6

Image 21 : 1-6 “Lessing House”
[image source]: Wolf Tegethoff. “Mies Van der Rohe: The Villas and Country Houses.” Richard Bacht Publishing. Essen, Germany. 1981.



3



4

1 This image is the original plan of Dexel House as designed by Mies Van der Rohe. Starting from the undimensioned layout, the author has chosen a module size 4 times the area of the small grid's module size.

2 The red grid overlays the original plan. At the medium resolution, the Dexel House is represented by a 7 x 7 grid.

3 The green lines represent the approximations to the original plan based on the medium grid. It overlays the grid and the original plan.

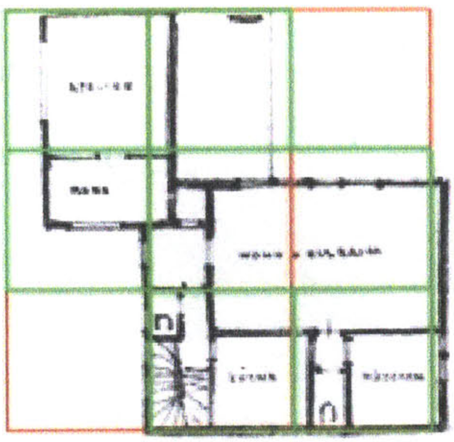
4 The green lines representing the approximation of the original plan overlays the medium grid.

5 The green lines representing the approximation of the original plan overlays the original architectural plan. It shows the accuracy of the approximated representation using the 7 x 7 grid.

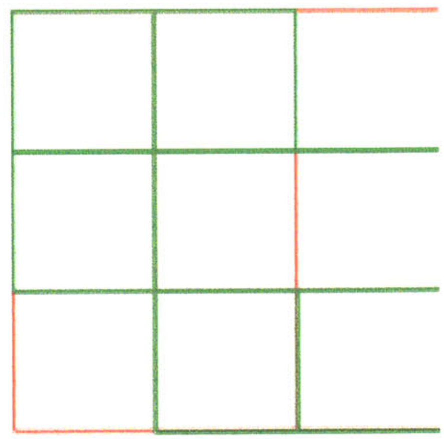
6 The new plan representing the original as an approximation using a 7 x 7 grid.

3.3 Crude Resolution - Large Grid

Image 22 : 1-6 "Lessing House"
[image source]: Wolf Tegethoff. "Mies Van der Rohe: The Villas and Country Houses." Richard Bacht Publishing. Essen, Germany. 1981.



3



4

1 This image is the original plan of Dexel House as designed by Mies Van der Rohe. Starting from the undimensioned layout, the author has chosen a module size 4 times the area of the medium grid's module size.

2 The red grid overlays the original plan. At the crude resolution, the Dexel House is represented by a 3 x 3 grid.

3 The green lines represent the approximations to the original plan based on the large grid. It overlays the grid and the original plan.

4 The green lines representing the approximation of the original plan overlays the large grid.

5 The green lines representing the approximation of the original plan overlays the original architectural plan. It shows the accuracy of the approximated representation using the 3 x 3 grid.

6 The new plan representing the original as an approximation using a 3 x 3 grid.

Intuitively, infinitely high resolution grids must provide the most accurate representations of the original plan. However, after analyses of Mies van der Rohe's Lessing House, Farnsworth House and Dexel House, it is clear that the resolution of the grid need not be extremely high while still capable of representing the key features of the original plan. Even though the Lessing House plan is most accurately represented by a 29 x 29 grid, its general characteristics can be represented in a 11u x 10u grid. Whereas the 7 x 7 grid offers a resolution so low its representation of the original plan is too abstract to be recognizable. The columns and walls of Farnsworth House can be generally represented by a 7u x 4u grid. Although the 4u x 2u grid is able to generally represent the walls, one might argue that the resolution it offers is not high enough to represent the columns. The Dexel House can be well portrayed by a 5u x 6u grid, while even a 3 x 3 grid offers an understandable representation.

Interestingly, a series of analysis performed on Palladian villas by Mitchell support the hypothesis that the low-resolution 3 x 3 grid as applied to Dexel House can offer a number of possible combinations in schematic plan layouts.

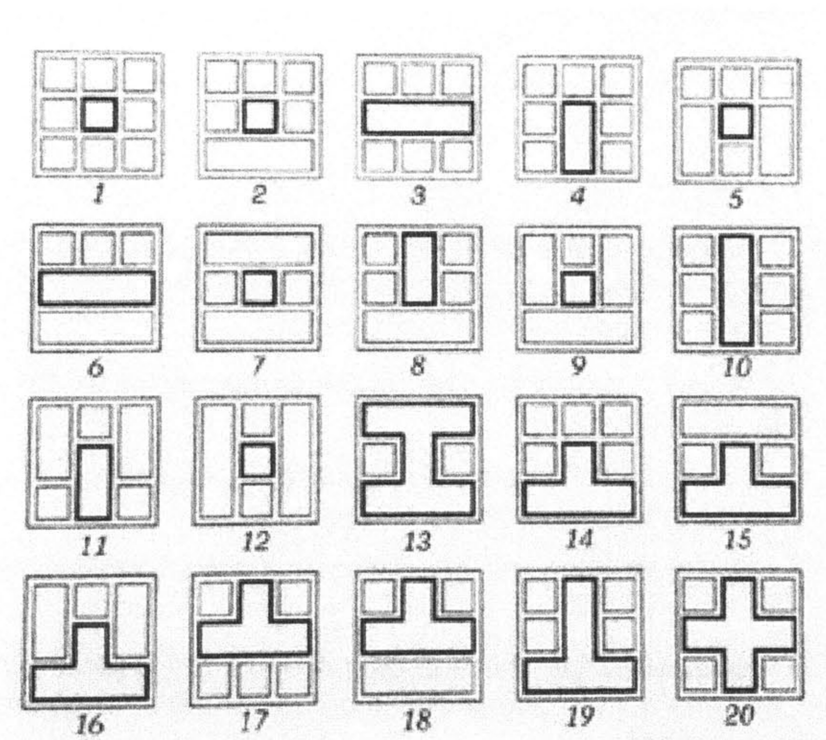


Image 23 : Twenty schematic plans represented by a 3 x 3 grid.
[image source]: Mitchell, William J. "The Logic of Architecture: Design , Computation, and Cognition." The MIT Press. Cambridge, MA. 1990.

The image 23 on the previous page is an enumeration of the possible schematic plans using a set of rules for bilaterally symmetrical tartan grids and for concatenation of individual grid cells to produce increasingly complex rooms. These rules are documented explicitly in The Logic of Architecture (Mitchell). Thus, with a 3x3 grid, it is already possible to create twenty unique "Palladian villas." The simple shape rules can be applied to larger structures with the increase of grid size. For example, the Villa Malcontenta can be represented by a 5 x 3 grid (Mitchell).

4. Villa Malcontenta by Palladio

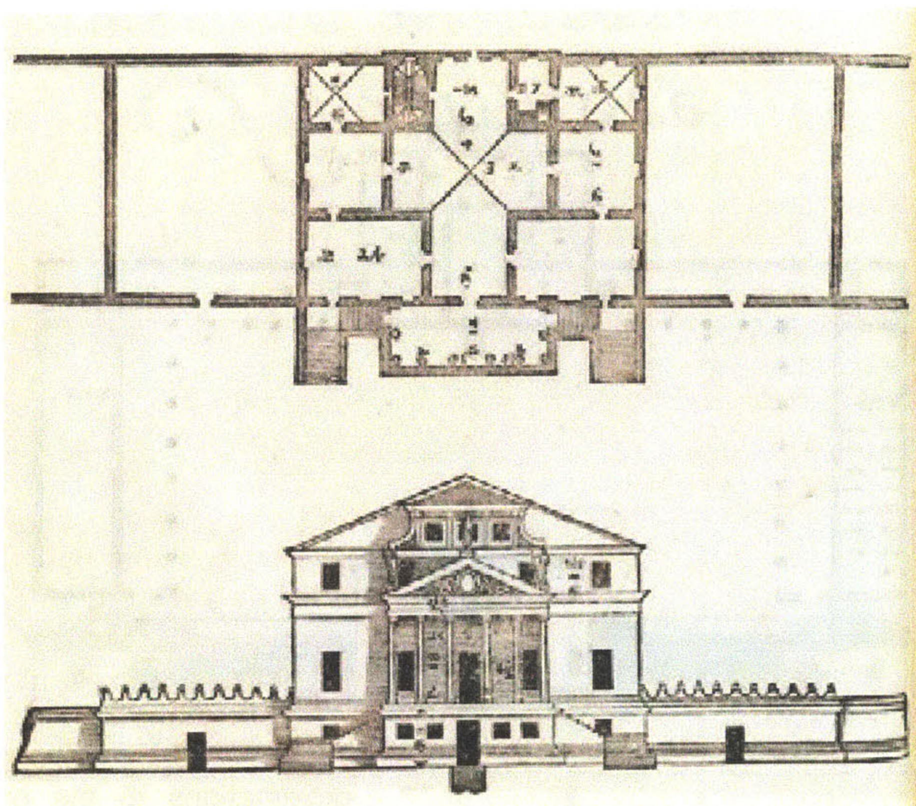
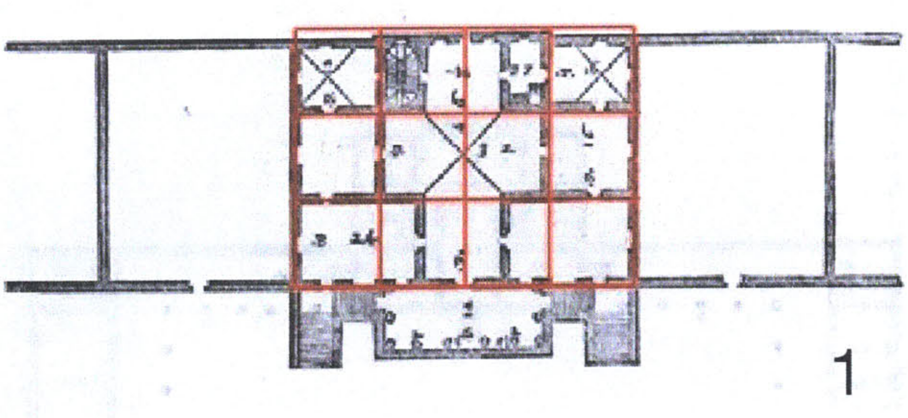
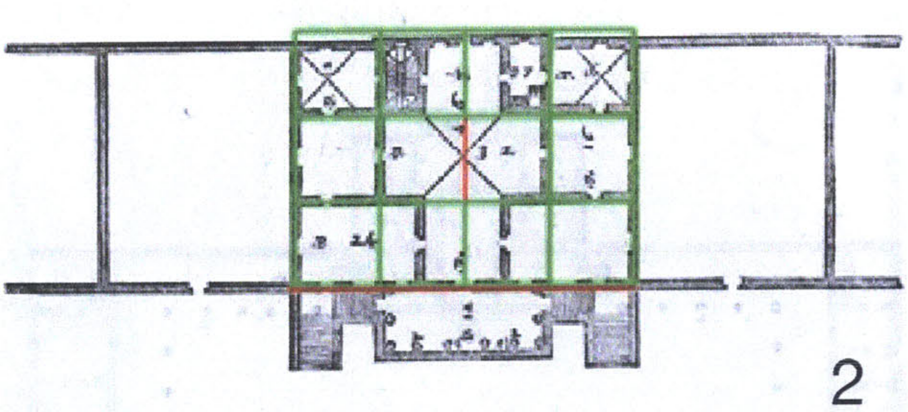


Image 24 : The plan of Villa Malcontenta by Palladio.
[image source]: Mitchell, William J.. "The Logic of Architecture: Design , Computation, and Cognition." The MIT Press. Cambridge, MA. 1990.

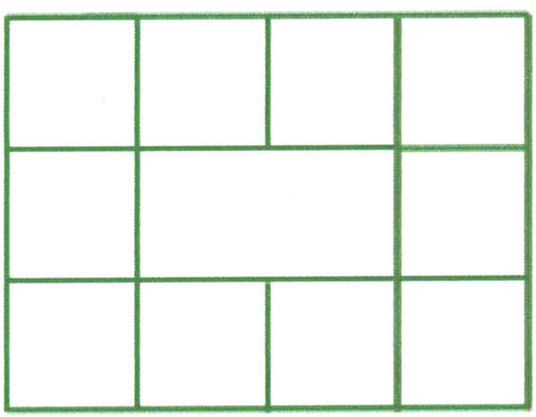
4.1 Villa Malcontenta with a 5 x 3 grid



1



2



3

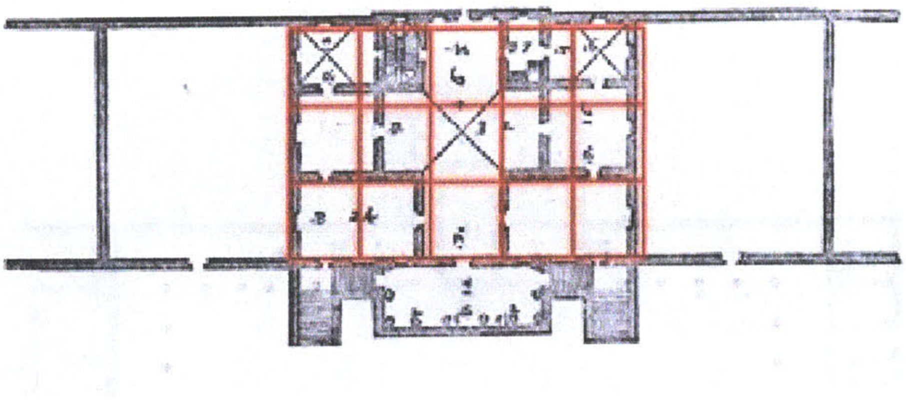
Image 25 : 1-3 "Villa Malcontenta"
[image source]: [image source]: Mitchell, William J.. "The Logic of Architecture: Design , Computation, and Cognition." The MIT Press. Cambridge, MA. 1990.

1 This image is the original plan of Villa Malcontenta by Palladio overlayed by a 4 x 3 grid. The smallest module size is taken from the smallest room.

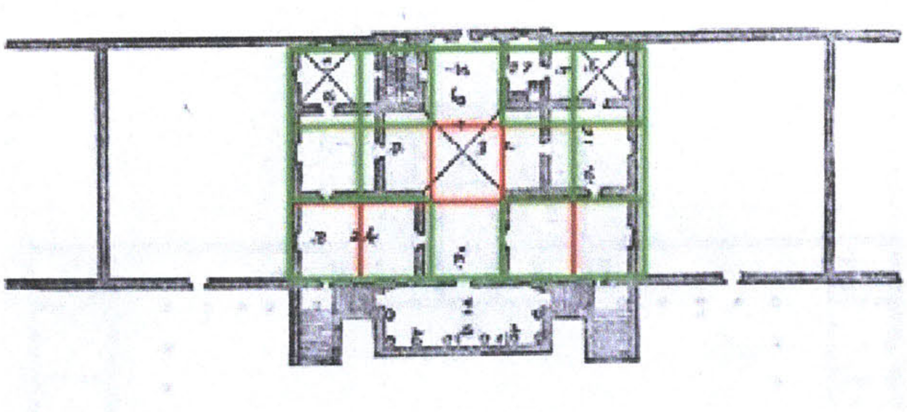
2 The green lines represent the approximations to the original plan based on the 4 x 3 grid. It overlays the grid and the original plan.

3 The new plan representing the original as an approximation using a 4 x 3 grid.

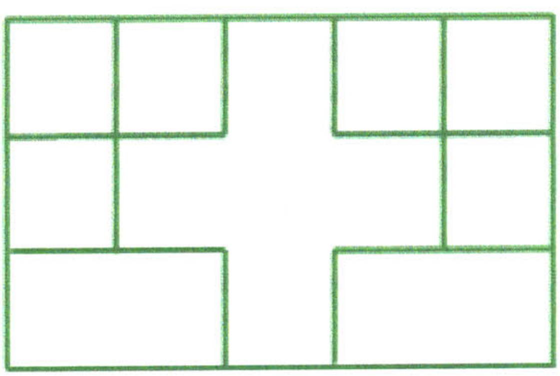
4.2 Villa Malcontenta with a 4 x 3 grid



1



2



3

1 This image is the original plan of Villa Malcontenta by Palladio overlayed by a 5 x 3 grid. The smallest module size is taken from the smallest room.

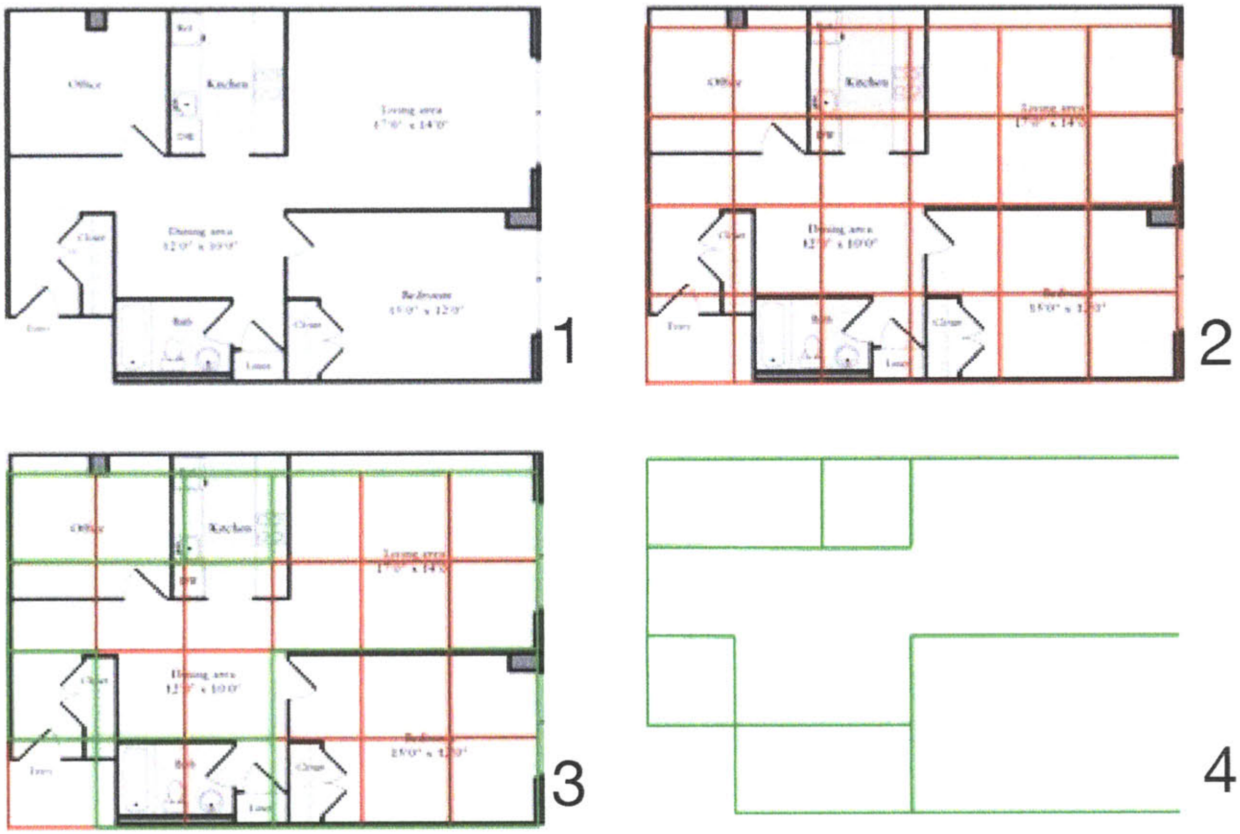
2 The green lines represent the approximations to the original plan based on the 5 x 3 grid. It overlays the grid and the original plan.

3 The new plan representing the original as an approximation using a 5 x 3 grid.

Image 26 : 1-3 "Villa Malcontenta"
[image source]: [image source]: Mitchell, William J.. "The Logic of Architecture: Design , Computation, and Cognition." The MIT Press. Cambridge, MA. 1990.

5. Analysis of Apartment Buildings

5.1 One-Bedroom Apartment



1 This image is the original plan of a one-bedroom apartment from Archstone in Kendall Square by the MIT Campus.

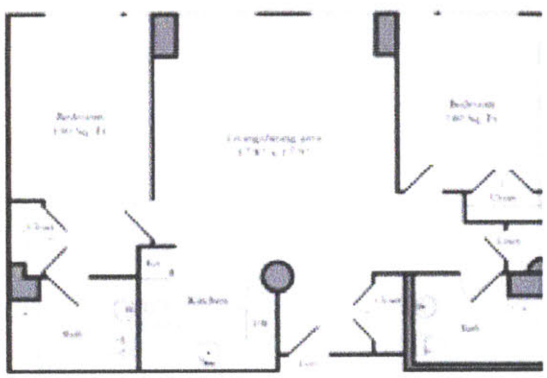
2 A 6 x 4 grid is sufficient to represent the plan of this apartment.

3 The green lines represent the approximations to the original plan based on the 6 x 4 grid overlays the grid and the original plan.

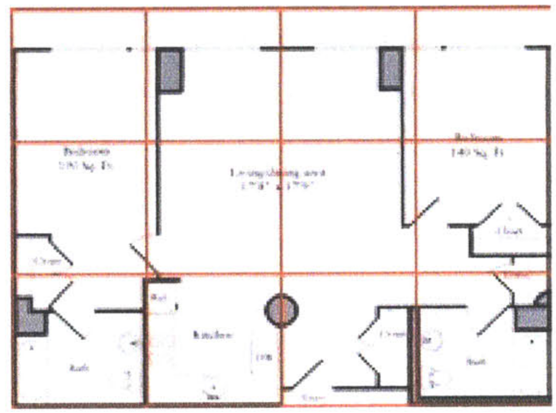
4 The new plan representing the original as an approximation using a 6 x 4 grid. From the analysis, the components of this apartment can be well represented with a 4 x 6 grid system.

Image 27 : 1-4 One-Bedroom apartment from Archstone Apartments.
[image source]: Archstone Kendall Square Apartments. One Bedroom J. url: http://images.equityapartments.com/media/ma_asnkendallsquare/Floor plans/KSQ_1I_1.1.O_950.gif.

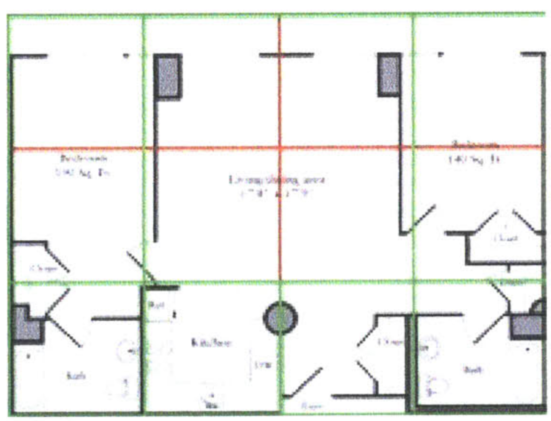
5.2 Two-Bedroom Apartment



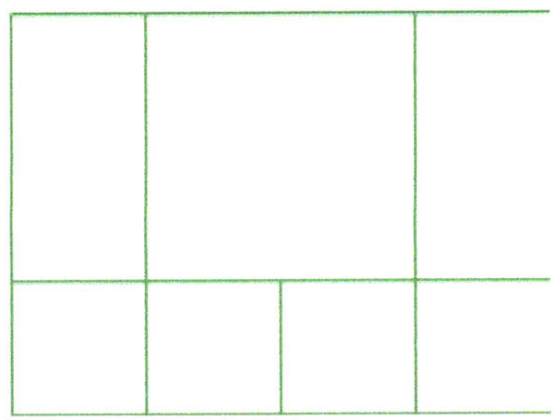
1



2



3



4

1 This image is the original plan of a two-bedroom apartment from Archstone in Kendall Square by the MIT Campus.

2 A 4 x 3 grid is sufficient to represent the plan of this apartment.

3 The green lines represent the approximations to the original plan based on the 4 x 3 grid overlays the grid and the original plan.

4 The new plan representing the original as an approximation using a 4 x 3 grid. Even though some components are lost due to low resolution, the resulting plan schematic is still able to represent the original plan as a whole.

Image 28 : 1-4 One-Bedroom apartment from Archstone Apartments in Kendall Square. Cambridge, MA.
[image source]: Archstone Kendall Square Apartments. Two Bedroom HH. url: http://images.equityapartments.com/media/ma_asnkendallsquare/Floor plans/KSQ_4B_2.2_1040.gif.

Simple floor plans designed without superfluous ornamentation or complex geometry can be generalized down to a grid system, in which each modular grid piece represents an enclose-able space. Through the analysis of the apartment complex plans, the proposed visualization machine for simple plans is applicable to the works of famous architects as well as modern residential apartment complexes. These analyses have also lead to the conclusion that meaningful floor plan schematics can be developed from very small grids. The original notion that one needs an infinite-sized grid to be able to represent a floor plan is rejected. After all, a 3 x 3 grid can generate twenty different combinations of floor plans for a Palladian villa, and a 4 x 3 grid is capable of representing a two bedroom apartment complex.

The grid system can be broken down into modular pieces. Reassembled, the pieces form a finite-sized grid.

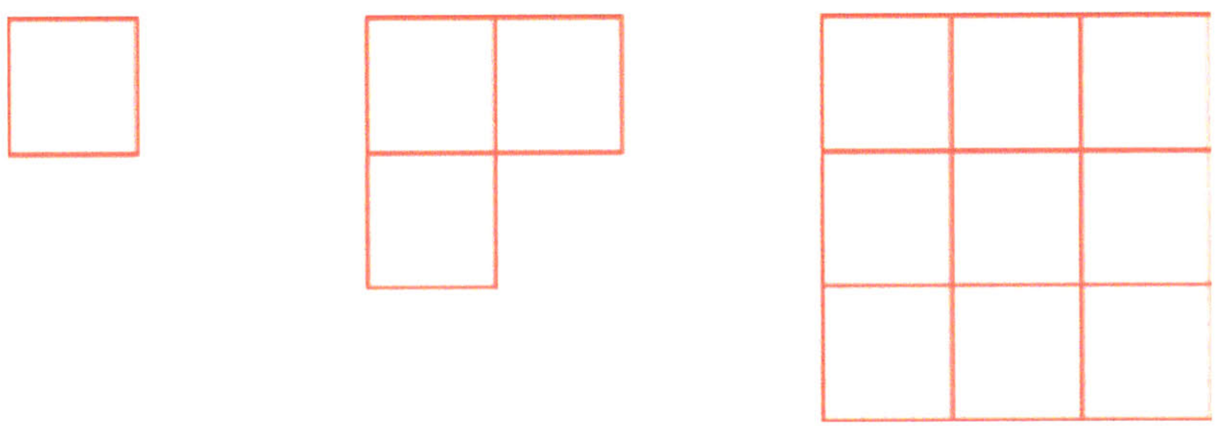


Image 29 : The grid system is composed of modular square units. The size of the grid can be modified by adding or subtracting individual modular units.

From the analyses of Mies van der Rohe's work it is determined that the important components of floor plans can be simplified to walls and columns. Therefore, each modular piece must support these components. The geometry of the plan will be represented by the extruded wall and column pieces of each module. Note that the 4 x 4 module arrangement below offers a 3 x 3 grid system. Similarly, a 5 x 5 module arrangement will offer a 4 x 4 grid.

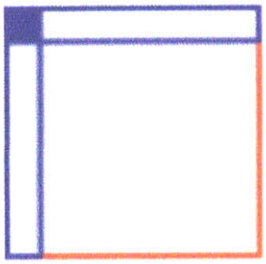


Image 30 : A single module for the machine contains 2 walls and 1 column piece. The two blue rectangles represent the wall and the shaded square represents the column.

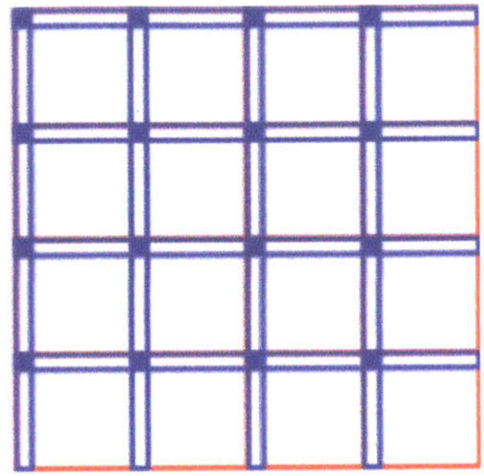


Image 31 : A 4 x 4 grid of the modules. A machine at this grid size should be able to well-represent simple Palladian villas, simple plans by Mies Van der Rohe, and simple apartment plans.

Chapter 3 : Hardware Components and Design

The imagined behavior of the tool is as follows. The user interacts with an interface in which he or she configures the floor plan schematic. Upon finalizing the room configurations, the selections of the user are saved, and the physical device moves quickly to reflect the floor plan designed by the user. The proposed physical mechanism is made up of two components : the physical device and the software. The software component of the tool is responsible for the user input; it's the part that users interact with to specify the schematic of the grid, and will be described in detail in the next section. On the other hand, the hardware of the tool is responsible for responding to the user input by moving the specified physical components to mirror the digital representation.

There are many factors to consider as part of the design process - economy, precision, ease of production, etc. Therefore, it is important to design the mechanism according to the specifications required by the most important factors in order to maximize its efficiency. Since limiting factors of the physical component are production time and the availability of tools and materials, the machine was designed to be fabricated with a 3D printer with ABS-plastic, a laser cutter, Plexiglas, and Masonite.

To begin the physical design of the device, the general mechanical ability of the device is established, and the most important features which are needed to represent an enclosed space is considered. From explorations in the works of minimalist architecture with a specific look into the floor plans created by Mies Van der Rohe in the Plans section of this book, it is determined that the most basic structural components are walls and columns. In Farnsworth House for example, Mies used eight cruciform columns as the predominate supporting structure for the rectangular building. At the end of the Plans section, the author proposed a modular system in which the grid is composed of individual, independent modules. The section is a discussion of the module and the design of its individual components.

1. The Module

The image 32 depicts a single modular piece of the larger grid. It represents a single grid component, or pixel, in the overall machine. It consists of two wall components along two sides and one column component in the corner where the two wall components meet. One module is composed of three motors and their respective holders, the wall and column components, the stand and base. Two tools are used in the fabrication process: the 3D ABS-plastic printer and the laser cutter. The head of the module, which acts as a holder as well as a guide for the wall and column components, is 3D printed for efficiency and speed. The image 33 shows the single module as the wall and column pieces are actuated.

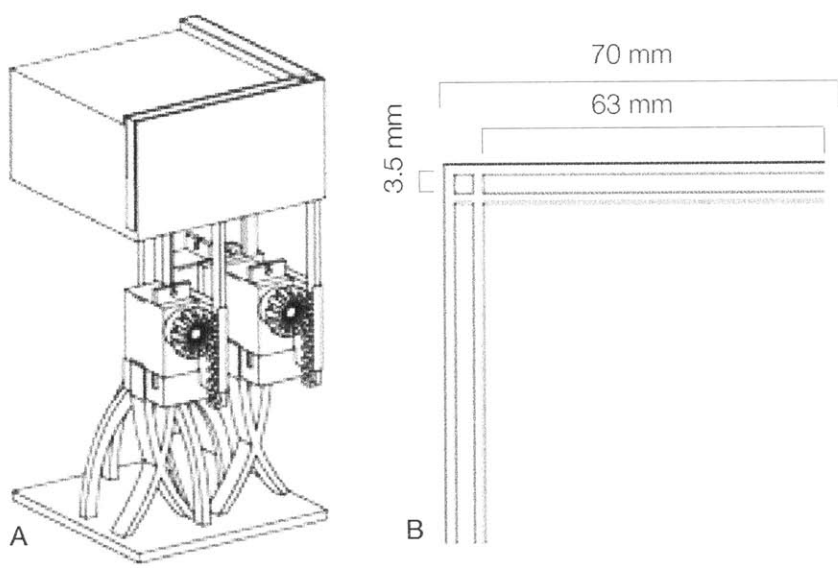


Image 32-A : One module of the larger grid system. This image shows all of the components belonging to a single module.

Image 32-B : All components - motors, holders, moving components, etc - all fit within the square boundaries of the head piece shown in this image.

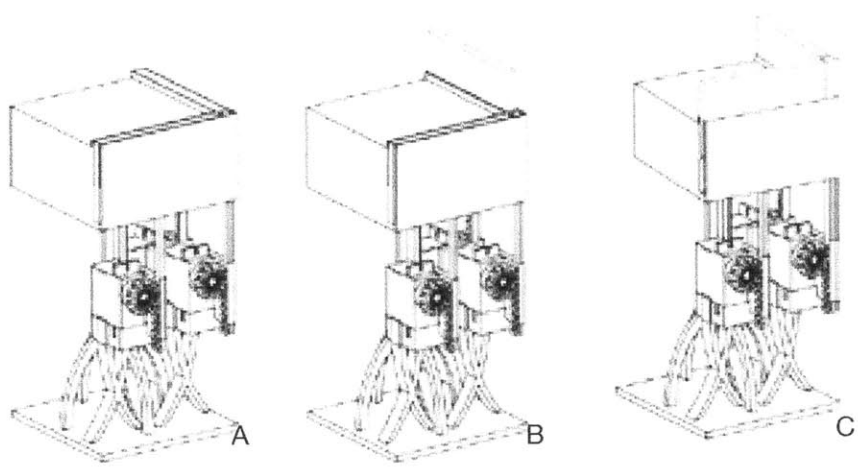


Image 33-A : The module in the resting position.

Image 33-B : The module as one wall component is actuated to the up position.

Image 33-C : The module when all wall and column components are actuated to the up position.

2. The Wall and Column Components

The wall and column components are the moving parts in each module. They are cut from Plexiglas sheets with 3 mm thickness by the laser cutter. The thickness of the Plexiglas used for these moving parts play a large role in the design of the head piece. In order for the wall and column components to be actuated, the slots in which these pieces are held must be just the right size, lose enough to allow movement without friction but tight enough to eliminate any non-linear movements. Through several tests with the 3D printer, it was determined that there must be a 0.5 mm tolerance interval to compensate for the inaccuracies caused by the 3D printer. For the Plexiglas of 3 mm thickness, the size of the slots' openings must be designed at 3.5 mm to allow for the desired actuation.

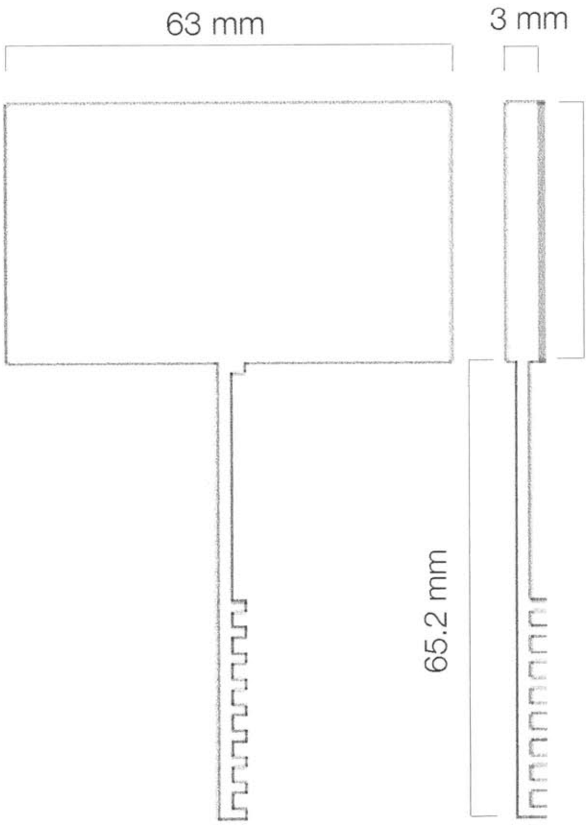


Image 34 : The wall and column components of the machine. (There are 2 wall components and 1 column component per one module.)

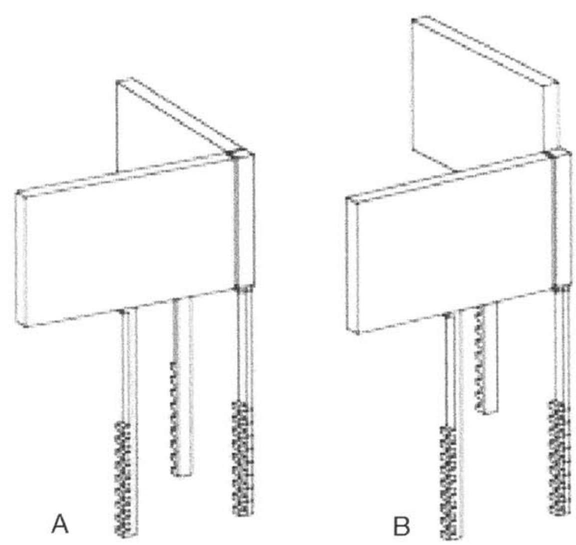
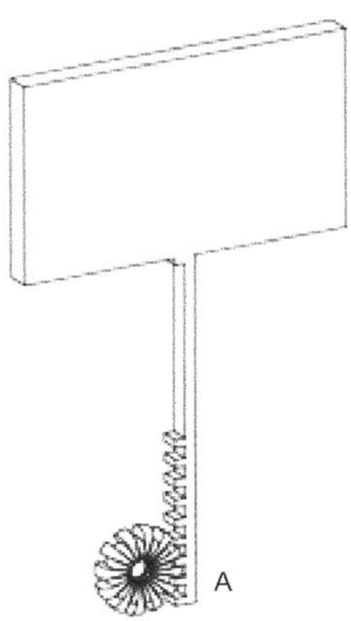


Image 35 : The wall and column components in the resting position (image 35-A) and with one wall actuated to the up position (image 35-B).

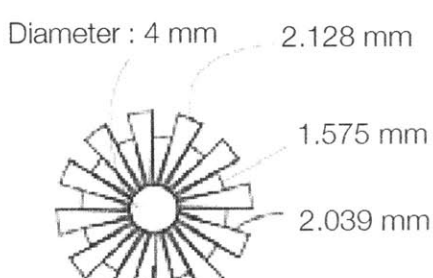
3. The Actuation Mechanism : The Rack and Pinion

The desired movement of the wall and column pieces is linear. Therefore, a simple linear actuator is needed to create this movement. The rack and pinion serves as the linear actuator for each of the moving pieces. They are specially designed to push each piece up from the resting position and pull each piece down from the actuated position. The rack is designed to be a part of the moving pieces so that the movement of each individual component is as smooth as possible. The rack and pinion actuating system is the most attractive because it is compact and can be easily constructed with cheap materials. The number of teeth on the rack and the gear is directly related to the desired height of actuation. Similarly, the length of the racks is related to the size and the number of teeth on the gear. The size of the gear is determined by the size of the servo motor; the gear has be no larger than the width of the servo motor, otherwise it will not fit within the bounds of a single module.

The size of the entire module, in fact, is determined by the size of the motors. Since there are three moving pieces, there needs to be enough room within a module component for three servo motors to fit. The size of the head of the module is the smallest size which still allows the three motors to fit under. This allows all components of a single module to fit within the xy-boundary of the head piece of the module.



A



B

Image 36 A : This is the rack and pinion as the linear actuator to move the wall and column components to the up position, and bring them back to the down position.

Image 36 B : The gear, dimensioned. The dimensions of the rack matches the dimensions of the gear. The motor rotate 180 degrees. At this size, the actuation system can move the components about 25 mm upwards.

4. Motor Components

The motor is responsible for the movement of the moving pieces, and it needs to be situated above the ground piece to be able to move the rack in a linear motion. A holder is designed to keep the motor above the ground piece. The holder has a inset slot which allows the motor to be press-fitted into it for a tight, secure fit. The stand is designed to snap onto the holder and press into the ground piece. Both the holder and the stand for the servo motor is 3D printed due to the geometry. The ABS plastic material used in the 3D printer is sturdy enough to withstand the vibrations given off by the servo motor during its movements. The holder also has a slot on the side to hold a backing piece which keeps the rack from moving away from the gear as the servo motor rotates the gear.

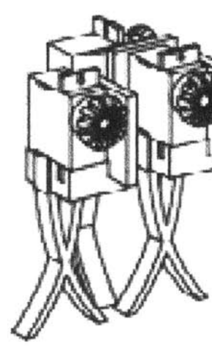


Image 37

Image 37 : The 3 motors along with their holders.

Image 38 A : This is the motor without anything attached.

Image 38 B : Motor with gear attached.

Image 38 C : Motor stand.

Image 38 D : Motor holder.

Image 38 E : Motor holder with stabilizing piece.

Image 38 F : Motor holder attached to the motor stand.

Image 38 G : Motor holder and stabilizing piece attached to the motor stand.

Image 38 H : A single motor unit assembled.

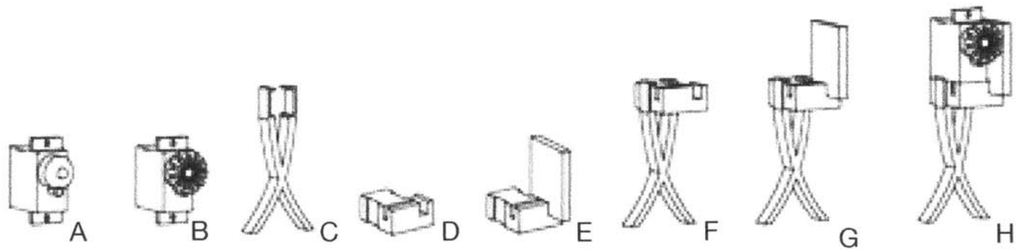


Image 38

5. Module Holder

The module holder needs to keep the module head above the ground piece. The square piece on top is fitted into the head of the module, and the legs of the stand are press-fitted into the square piece, allowing for a tight fit. The legs also press-fit into the ground piece. The module holder is laser cut out of Masonite, and the design of the legs makes the holder strong enough to withstand the movements of the wall and column components and holds the motor stand in piece as the motor actuates the movements.

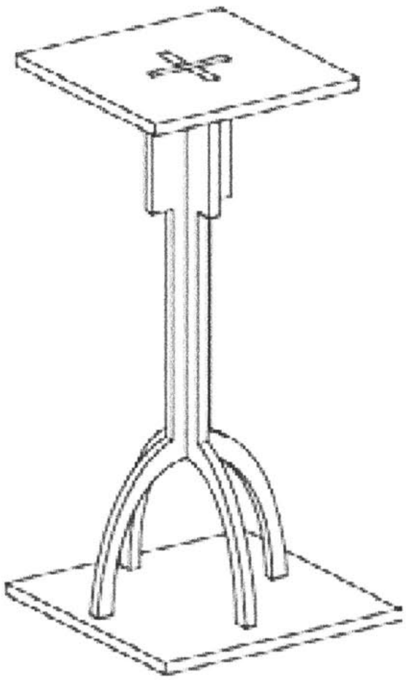


Image 39 : The holder for the module.

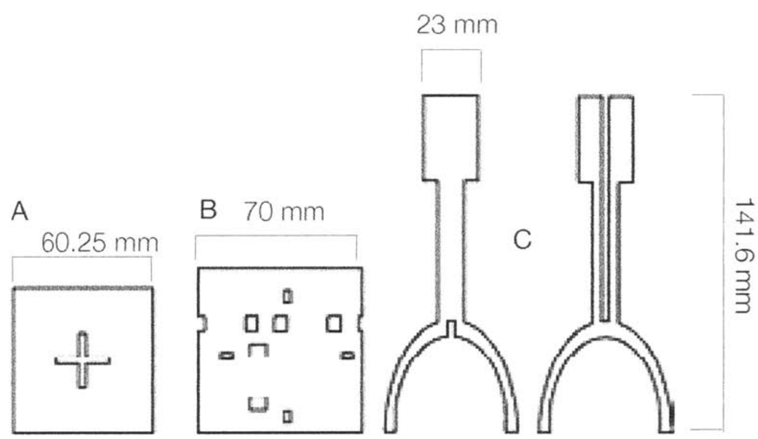


Image 40 A : The piece that fits into the module's head.
Image 40 B : The ground piece that holds all pieces together.
Image 40 C : The legs of the holder. They fit together link a puzzle.

Chapter 4 : Software and User Interaction

The software portion of this project is created in collaboration with Takehiko Nagakura (Ph.D), the advisor for this thesis project. Written in Processing, the software contains a representative, user-facing component in addition to the functional component responsible for controlling the servos. In order to interface with the Arduino hardware, the ServoFirmata firmware is first uploaded to the micro-controller. Firmata is a part of the Arduino software package; it is a generic protocol for communicating with micro-controllers from software on a host computer, and is available for download from http://firmata.org/wiki/Download.

The user interaction reflected in the physical components of the visualization system is made possible through communications between Processing and Arduino. The Processing IDE is ideal when trying to program micro-controllers. It is used to visualize the physical component and accept user input through mouse clicks. Before running the software, the user must specify the grid size of the architectural plan and set a small delay time between the actuation of each consecutive servo motor. Once the software is run in Processing, the user is presented with a graphical interface which represents the physical model in digital form. In the interface, the user can select from a number of actions in a menu on the left hand side: move all motors to the ninety degree position, move all pieces up, move all pieces down, toggle between simple view and pin view, load previously saved plans, and save the current plan. The user can assign Arduino pins to each individual moving piece through a text file related to a saved grid, and control each piece through the graphical interface. The Arduino micro-controller is used for signal processing. It listens for digital signals sent from Processing, parses it, and outputs the appropriate signal to the physical components.

Together, the software and the micro-controller creates an integrated system that maps physical layout to the digital interface. When the user clicks on the rectangles on the screen representing a specific physical piece, the corresponding physical piece moves in response.

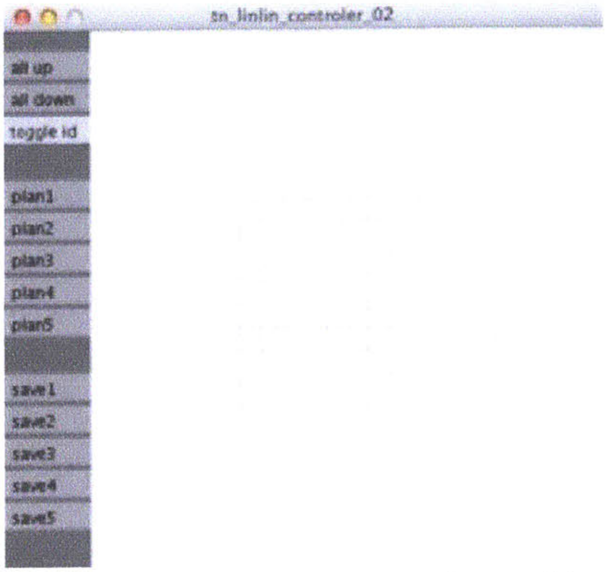


Image 41 : A 2 x 2 grid as seen on the user interface.

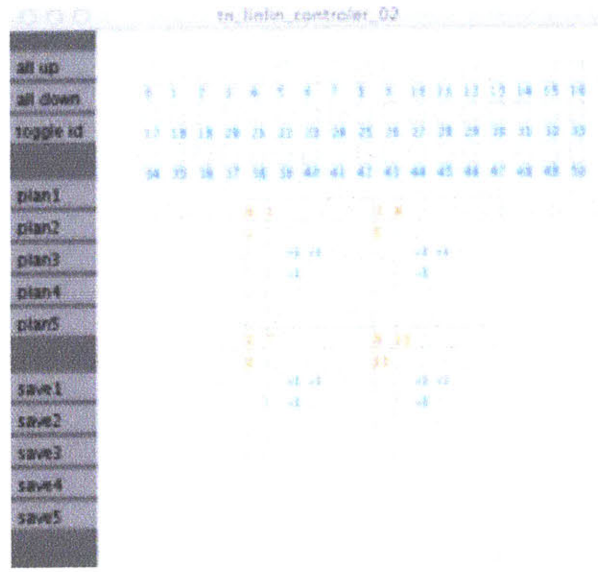


Image 42 : The same 2 x 2 grid showing the IDs of each piece. The values 1 and -1 signify that the corresponding motors have not been assigned yet.

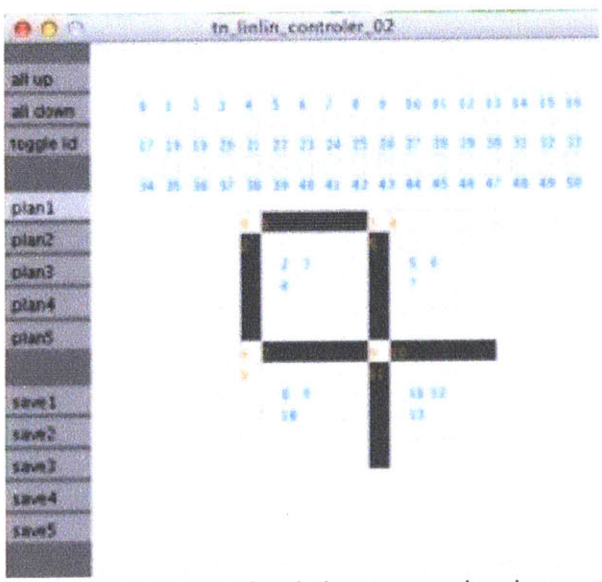


Image 43 : Loading plan 1 shows a previously saved plan. The darkened wall pieces are those that are in the up position, as chosen by the user. Notice that the blue numbers are no longer -1 or 1. This means motors have been assigned.

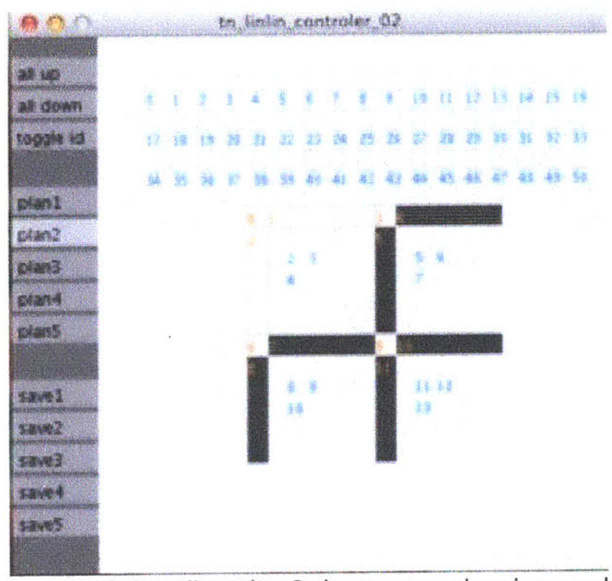


Image 44 : Loading plan 2 shows a previously saved plan. The darkened wall pieces are those that are in the up position, as chosen by the user. Notice that the blue numbers are no longer -1 or 1. This means motors have been assigned.

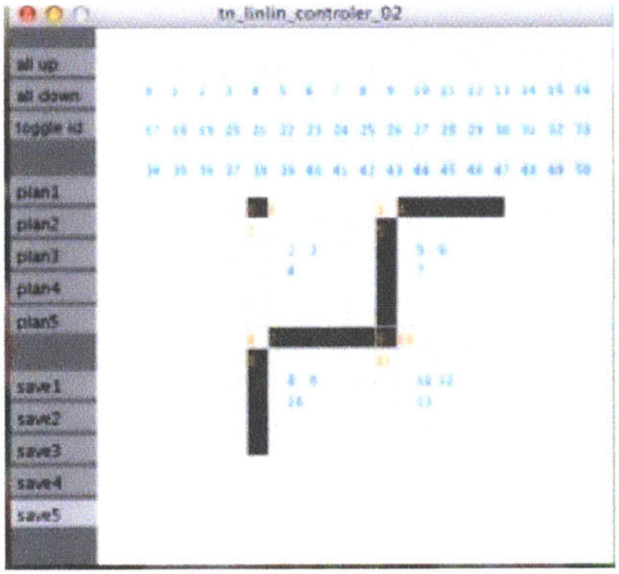


Image 45 : Saving a plan after the user has specified which wall and column pieces (darkened) are to be in the up position.

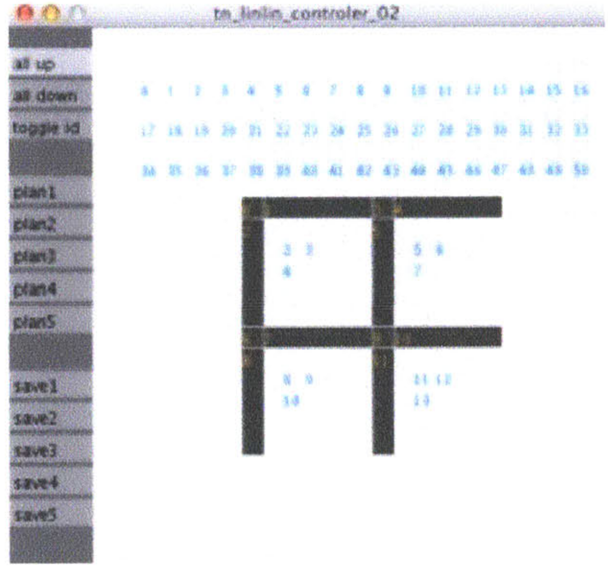


Image 46 : Actuating all of the moving components in the 2 x 2 grid to the up position.

```
import processing.serial.*;
import cc.arduino.*;
Serial port;
Arduino arduino;
// variables you want to change
int xtile = 2;
int ytile = 2;

int action_delay_milsec = 10 ;
```

Image 47 : The xtile and ytile parameters are changeable parameters. The user can set the size of the grid. The circled components are the only values that the user needs to change. The action_delay_milsec parameter is the delay time between the movements of each motor. A lower value will make all pieces appear to move at the same time. However, this is taxing to the Arduino, because it uses more power to move more pieces simultaneously.

```
import processing.serial.*;
import cc.arduino.*;
Serial port;
Arduino arduino;
// variables you want to change
int xtile = 4;
int ytile = 4;

int action_delay_milsec = 10 ;
```

Image 48 : Increases the size of the grid to a 4 x 4 grid.

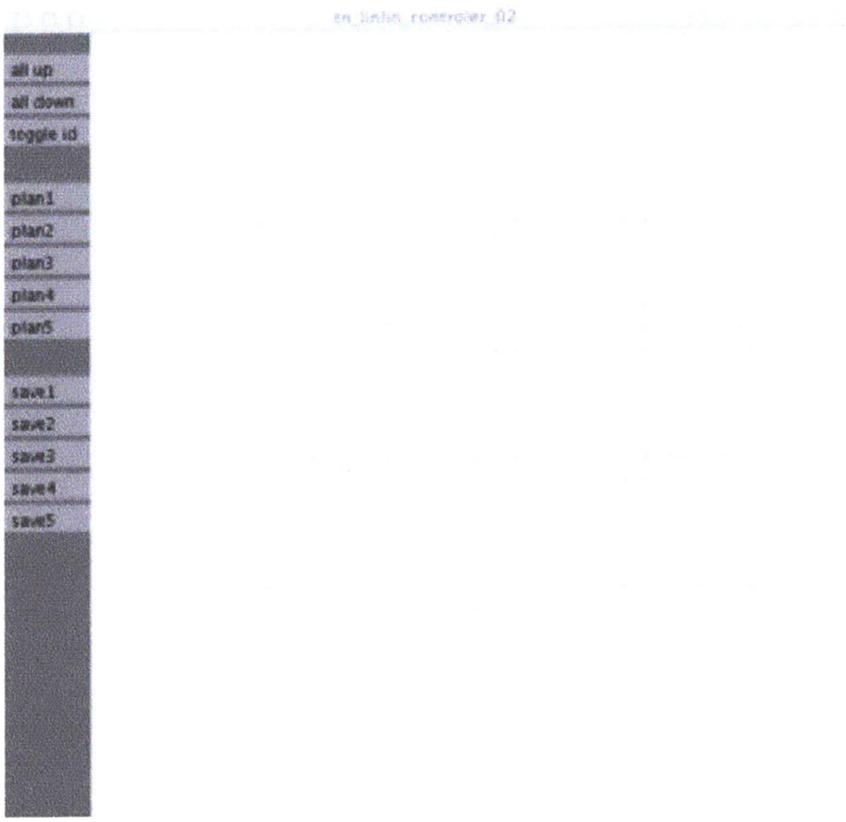


Image 49 : The 4 x 4 grid as seen on the user interface.

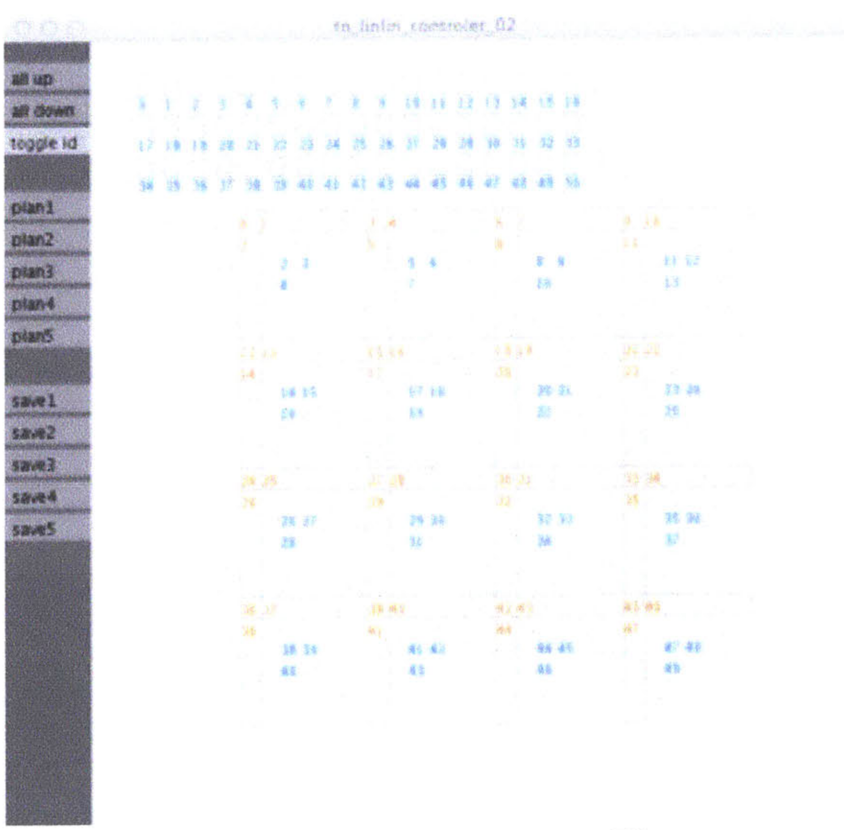


Image 50 : The 4 x 4 grid with respective IDs set to each moving piece with assigned motors.

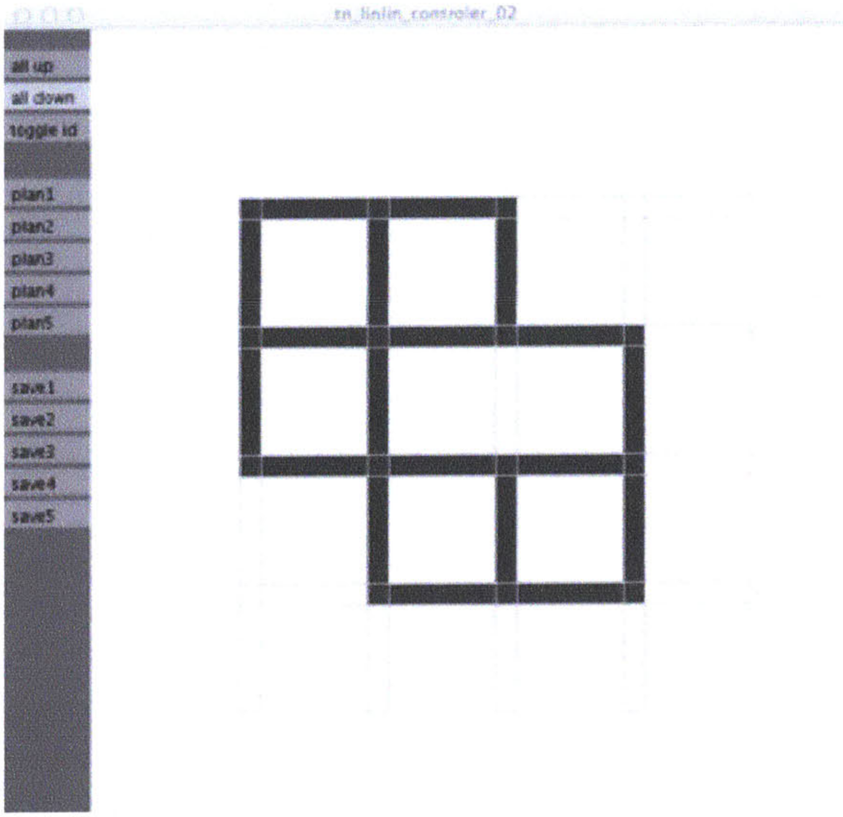


Image 51 : The machine and its software can reproduce the 3 x 3 grid-size approximate plan of Dexel House using a 4 x 4 machine-grid. (Compared to the original image 22-6 on page 38.)

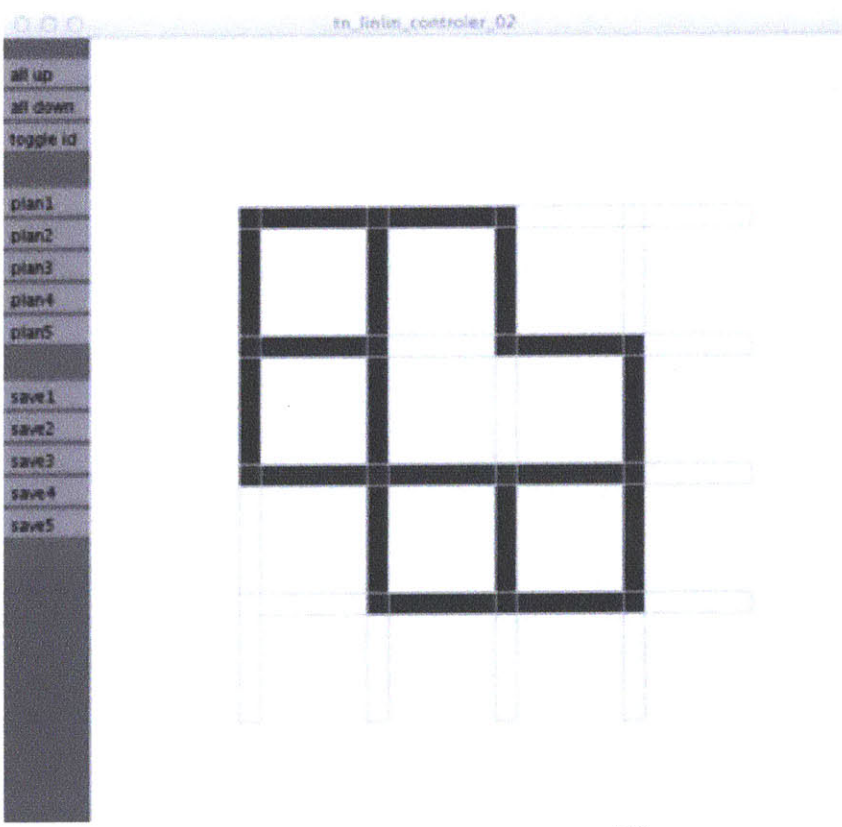


Image 52 : The user can change the machine visualization of the Dexel House plan by quickly changing the wall and column selections on the virtual plan of the machine's user interface.

Chapter 5 : Conclusion and Future Explorations

The proposed design visualization machine to be used as an agile prototype for architectural plans on a finite grid is successful in offering flexibility and quick visual feedback to rapidly visualize simple plans. The analysis of Ludwig Mies Van Der Rohe's plans, Palladio's plans, and apartment building plans suggest that a 12 x 12 module grid on the machine, or a 11 x 11 visual grid, is sufficient to approximate simple architectural plans. The scalability of the system allows the user to visualize plans of various complexities. The user interface provides an easy way for users to modify plans and see their modifications immediately. The integrated machine allows for flexibility in design and rapid feedback during modifications, saving time and effort for designers in the prototyping process.

1. Improvements

The design of the machine can be improved to make the fabrication process much simpler and improvements to the holding mechanisms can also correct occasional failures in the actuation process. The module's head component is 3D printed with ABS plastic. Currently, it takes about 3 hours to print a single head module. Modifying the design of the head component to contain only the parts which guide the moving wall and column components and discarding the extraneous side planes will significantly speed up that fabrication time. Instead of printing the extraneous side planes, it is possible to achieve the same effect by gluing laser cut pieces to the 3D printed part. The proposed modification is shown in image 53.

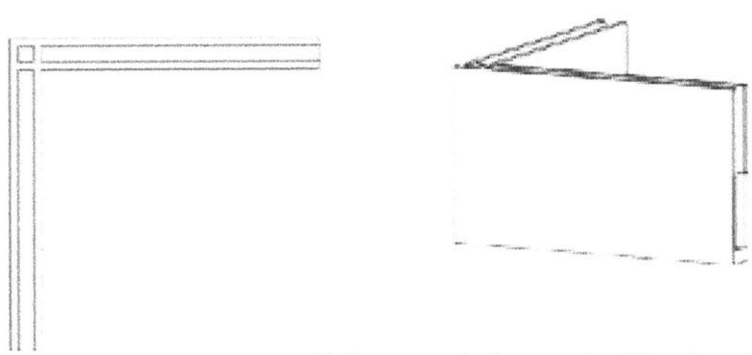


Image 53 : The proposed alternate design to the 3D printed module head piece.

The height of the module holder as well as the height of the motor holder can be decreased. The current system uses a press-fitting technique to keep all the pieces secure. However, due to the amount of vibrations given off by the motor during the actuation process, it is not sufficient to tightly keep the module components from moving. In order to eliminate the effects of the vibration, the design should experiment with using bolts and screws to secure the legs of the motor and module to the ground piece.

Furthermore, the rack and pinion actuators should be refined to be more accurate. In the current system, the backing piece inserted into the motor holder prevents the rack from moving backwards off of the gear, but it doesn't not correct against lateral movement. In this iteration, the rack slips off of the gears on the motor due to the vibrations. Paper clips are used to temporarily act as a guide to keep the racks from slipping off. Once the rack slips off of the gear, the corresponding wall or column piece fails to move up until the rack is pushed back on to the gear. With the current size of the grid, fixing this mistake is time consuming and requires much effort to correct. It is necessary to design a motor holder that keeps the rack and gear always engaged.

Finally, in this iteration of the machine, several components are fabricated by using the 3D printer. Even though the 3D printer offers benefits for the project – strong components, speed – it is difficult to design pieces which require a perfect fit to operate. The pieces produced by the 3D printer is never the same. As a result, the fit of each component varies: some are too tight and some are too loose. The trade-off of using the 3D printer versus another fabrication machine, such as the laser cutter, in this case is speed. However, if there was more time for the production of this machine, the trade-off is worth it. The machine would have less failure rate due to fitting issues.

2. Future Explorations

Each of the moving pieces has its own actuating component. There are 48 moving pieces in the 4 x 4 module grid on the current iteration of the machine. This "brute-force" method requires one motors for each moving component. This makes the fabrication and assembly process of the machine extremely time consuming and error prone. As the number of moving components increase (with larger grids) the number of modules will also increase. Therefore an innovative method to create the linear movements required by the moving wall and column components without using one motor per moving piece is needed. By decreasing the number of motors, the circuit design will also become less complex.

Once an alternative method for actuating the moving pieces is developed, the design of the wall and column pieces can be modified to be more than one material (ie: a clear wall and an opaque wall). The user can choose the type of wall material to use for any section of the plan, leading to increased combinatorial representations to visualize designs. The shape of the column pieces could be cylindrical as well as rectangular, just as there are cylindrical and rectangular columns in real architectural plans.

Photos of the Visualization Machine

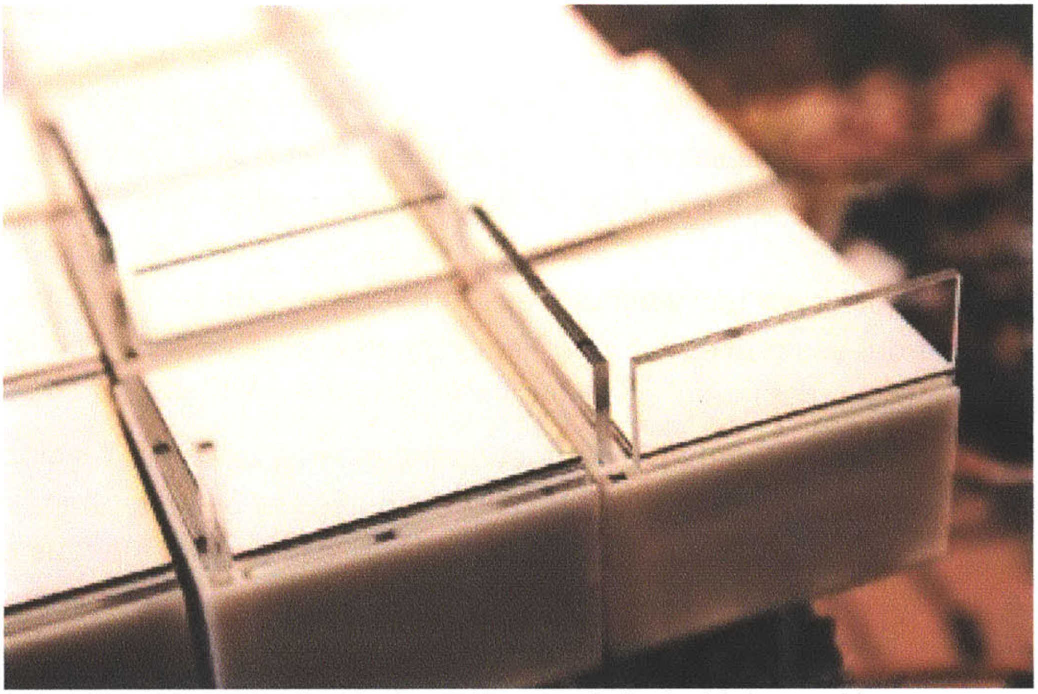


Image 53 : Actuated wall and column pieces on th 4 x 4 grid size machine.

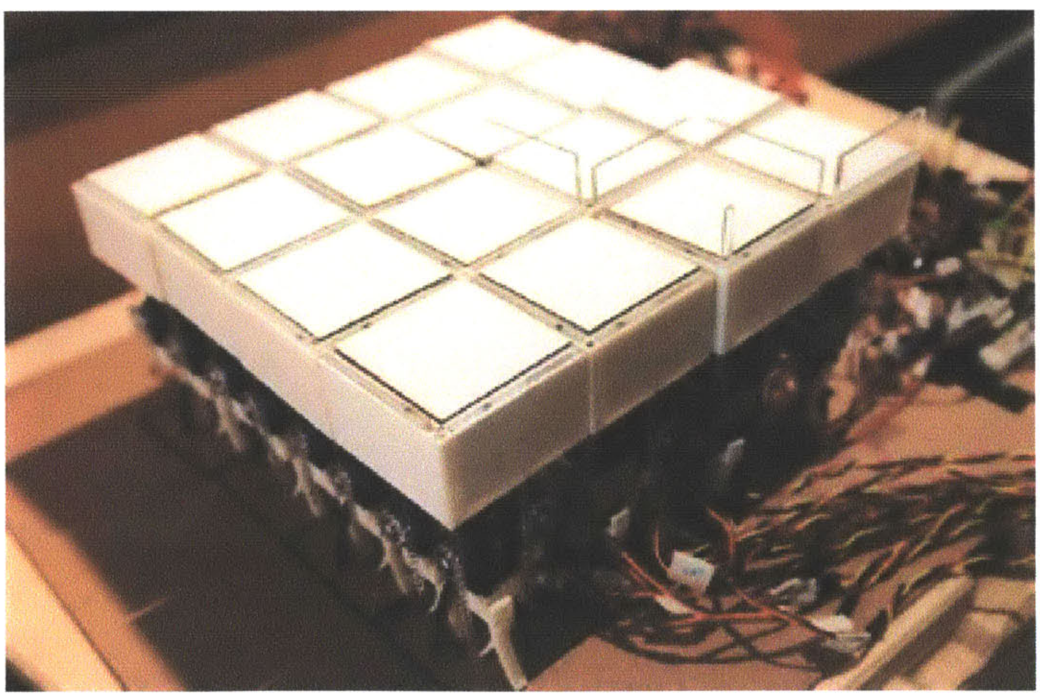


Image 54 : The 4 x 4 grid machine.

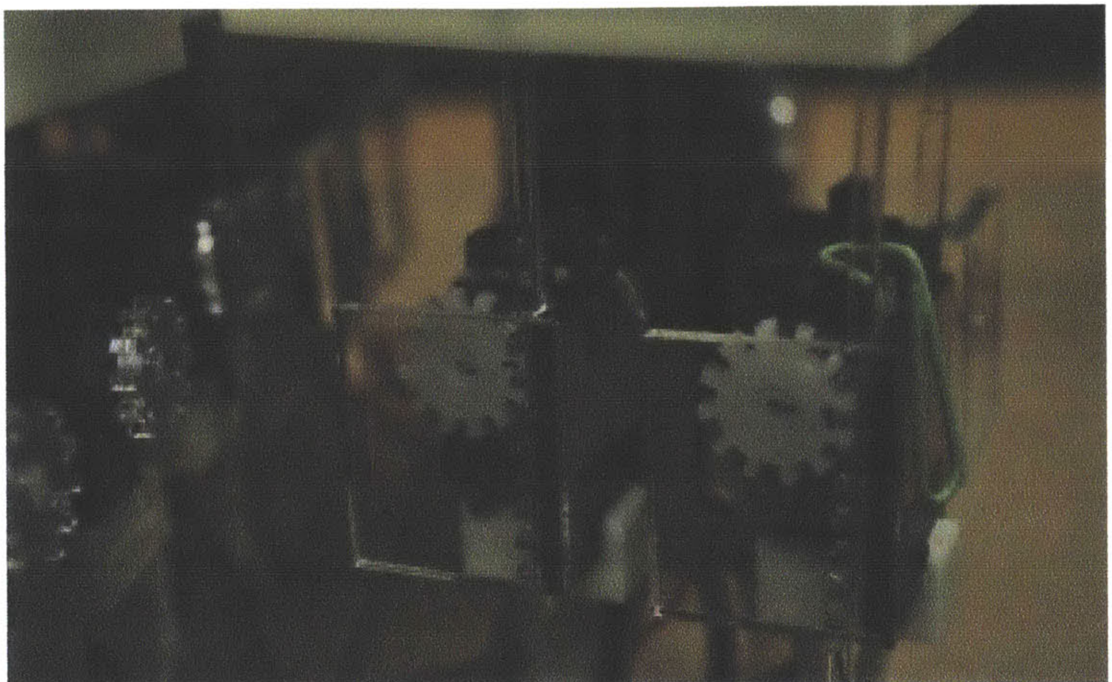


Image 55 : A close up of the motor pieces. The paper clip is to correct for any lateral movement of the rack.

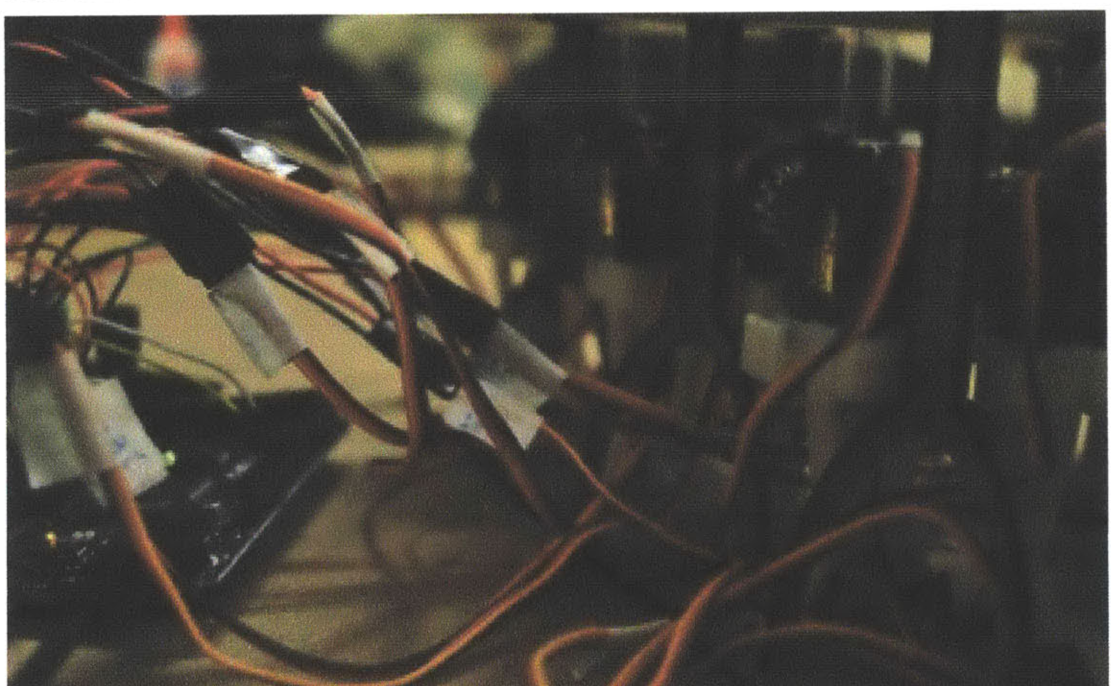


Image 56 : The electrical wiring of the motors in the 4 x 4 grid machine is difficult to organize.

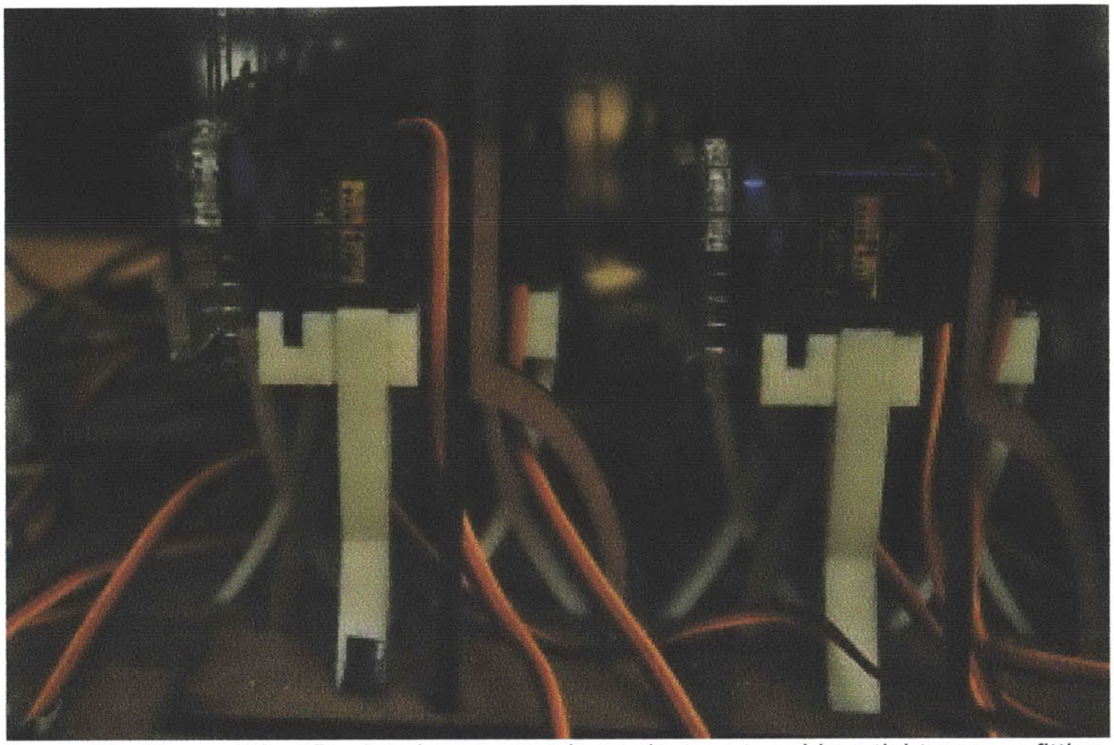


Image 57 : Some of the 3D printed motor stands require tape to achieve tighter press-fitting.

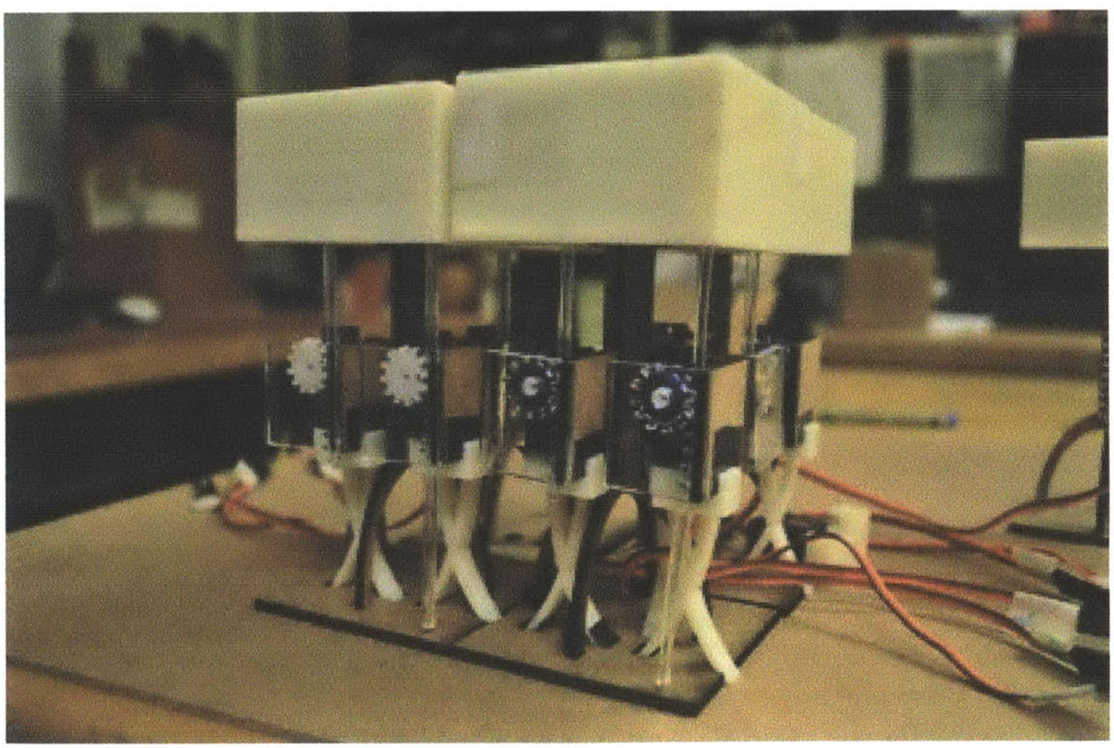


Image 58 : A 2 x 2 grid.

Image 59 : The completed 4 x 4 grid machine with actuated wall components, controlled by the computer.

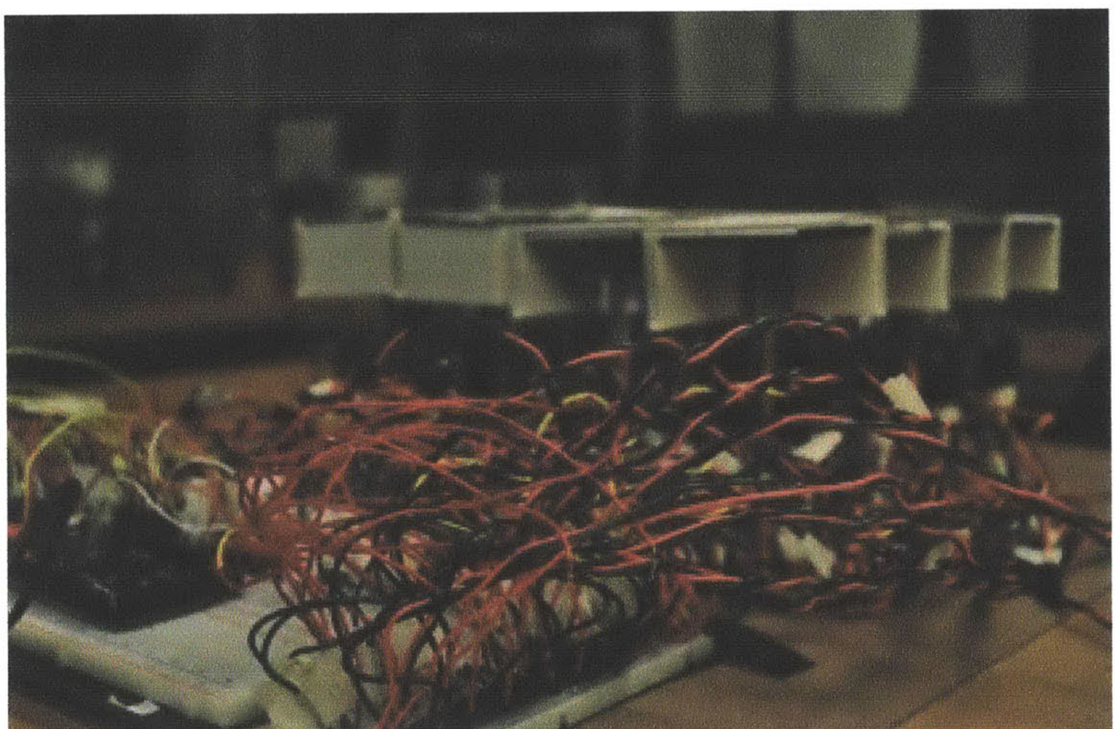


Image 60 : The wiring of the machine.

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