Design for Self Assembly of Building Components using Rapid Prototyping

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Design of assemblies will become an area of study when using rapid prototyping devices in the architectural design process becomes standard practice. This paper is a presentation of a design process study focused on understanding a method of working with rapid prototyping devices in a creative design process. This paper has an emphasis is on the creation of physically large models. These models are built from many layers of detail and are too large to print on a conventional 3D building device (3D printer). In response to this is a proposal to design assemblies as a means to create models of parts manufactured with rapid prototyping devices. Design for Assembly (DFA) becomes an exclusive process within this method of model making. Designing assemblies as part of a creative design enterprise offers greater knowledge of the building’s construct at an early stage of the process. As an example, there are three physical models built from 3D CAD descriptions for this study. These models are manufactured from various rapid prototyping devices and differing processes of assembly. They are evidence of DFA as a necessary process in architectural design when using rapid prototyping devices.

Keywords: Digital Fabrication, Design Methods, Design for Assembly.

Introduction

This paper demonstrates methods to physically build large design representations of varying materials on three different types of rapid prototyping devices. The motivation is to define a method to embed assembly mechanisms between manufactured shapes. There is no specific type of shape referenced in this paper. The focus is on connecting many smaller shapes to create one large physical representation of a shape after a topological division is declared. The topological variation is based on device manufacturing time and the size of the device envelope.

Self-assembly is a biological term defining a method to construct structures whose complimentary shapes cause them to aggregate into a desired structure. The method is used to control complex three dimensional structures. Michael Ward defines five steps in the process used to design self assembling molecule: (1) predict a structure, (2) design a system (3) fabricate a system (4) study the structure
Architects’ recent inquiries into the use of rapid prototyping in practice and studio determine that it is possible to build designs quickly using processes such as 3D printing and laser cutting. Large representations of designs on paper or in physical form as models are critical to a design process. When using 2D representation architects enlarge technical drawings, such as elevation drawings of facades and plans to a scale of 3\" = 1\' from drawings that start at scales of ¼\" = 1\'. This scaling operation is difficult when using rapid prototyping. In both cases—drawing and model making—objects created as macro scale (¼\" = 1'-0\") are not easily scaled to the micro (3\" = 1'-0\") without the addition of a more information or by dividing the part into many smaller pieces joined by an assembly procedure. The question is how to quickly build many models of complex shapes of sizes larger than the envelope of most rapid prototyping machines.

The design process in this paper is a creative endeavor verses an engineered process of problem solving. The creative process is best described by T B. Ward, et al. as an initial generation of candidate ideas followed by an extensive exploration of those ideas. Ward et al. refers to creative imagery and the central role it plays in creative functioning. The key component in the work in this paper is creativity and its relationship to a generative process of building candidate designs/ideas. In the case of architecture this refers to candidate designs in the form of rapid prototyped models. Ward’s process of studying creativity and cognitive learning is a broad overview of studies and methods to understand how artifacts do or do not lead to the generation of new ideas.

On the issue of model size, I would argue here that current design methods that incorporate the use of rapid prototyping to build small models do not aid the process of spatial or formal exploration in architecture. Design architects work with simple representations, often only confirming spatial gestures such as the overall shape of a building or challenging internal spaces through the use of hand made large models or large drawings. Architect Frank Gehry prefers large scale models whose physical representation can range in sizes up 6 feet in height. As described by Mitchell, “automobile designers as well as architects such as Frank Gehry prefer to sketch or sculpt using standard physical media as a method to maintain design speed and freshness” (Mitchell, W J. 2001).

**Related Work**

There have many papers and books written on the application of rapid prototyping in architecture. These publications focus mostly on a rapid prototyped model as the final representation of a single design idea. Few refer to these models as part of a generative process. Rapid prototyping for architects was introduced by Mitchell (Mitchell, W. 1995) as a method of translating three dimensional models in CAD to NC processing for building fabrication. The concept of manufacturing architectural ideas is described by Ryder, et al. as a method of physically building design ideas for rapid manufacture using seven differing types of rapid building devices from stereo lithography to selective laser sintering to 3D printing. This paper is a survey of processes and some application methods in architecture. Included are methods to use a shape grammar process to generate models that can be fabricated on a 3D printer for use in the earlier phases of design (Wang, Y).

Shortcomings in all three methods either discussed the limitation in model size based on the machines’ build or milling envelope, or prescribed alternative uses with larger machines. The shortcomings in relationship to the process of creative design are in manufacturing time between the representations of each design. Most rapid prototype machine envelopes are 10\"-12\" cube. There are others whose envelope is as large as 20\" cube. Cost for larger models is very high. In addition the time to manufacture each design representation is very slow.
Smaller envelopes mean a limit in model size if printed in one piece.

Assembly of parts is needed when the goal of design modeling and fabrication is focused on the making of physical models of a size larger than the envelope of rapid prototyping devices. Much has been done in the field of assembly design with areas of interest that can be linked to architectural design when using rapid prototyping devices. Parametric assemblies as they relate to architecture are presented by K. Nassar who relates materials during construction as a means of design constraints (Nassar, K., et al.). He notes that material dimensions limit geometrical representation where materials and computational operations are stored in a library for easy reference calls. Assemblies of geometry are tangential, not interlocking or mechanical. Assembly is referred to as a means to attach geometries.

**Fabrication functions**

Creativity is defined as a generative process by Ward, but here it is a process that uses physical modeling verses paper to build candidate ideas for design reflection (Schon1983). Creative fields that produce products as candidate ideas-song writing, sculpture, fashion design and product design-incorporate the time and space to fabricate candidate ideas. When using pencil this space is defined as drawing or sketching time where paper setup, pencil sharpening or shading a drawing to make shadows are functions that fill time. Fabrication is the time delay between the moment of evaluation between each candidate idea in a process. Here the space used to design assemblies, manufacture parts, and assemble candidate designs is referred to as a fabrication function. There are two functions as part of the process of design when using rapid prototyping device: design function and fabrication function (figure 1).

Design automation has been made clear by many who attempt to develop faster ways to create design descriptions. Gero discusses systems of design that incorporate function, structure and behavior within a knowledge based system to produce designs. A user of the system is guided through the process by various forms of CAAD knowledge. The resulting representation was created from stored information reused to generate a new representation (Gero 1990). Stiny’s production method uses shape rules and algebraic functions to generate shapes and replace those shapes with new shapes (Stiny 1990). Both methods are generative in nature and result in design descriptions in the form of drawings or virtual models. However, Stiny’s method is based on ambiguity within a fixed grid and Gero’s methods are based on the user’s ability to reuse explicit knowledge.

When using rapid prototyping to fabricate architectural models it is preferred the models’ CAD representation be reduced to fit within the build envelope of the device 10” x 8” x 8” maximum model size (figure 2). In order to decrease the time taken to generate candidate designs the model is reduced in size. In other words, little time is needed to process a design description for fabrication other than the time it takes to scale the geometric model. Sometimes the geometry is changed in order to create a robust print of the type in figure 2. In this case the model is reduced in scale to fit the printer,
parts too thin to manufacture are thickened. To build
designs larger than the device envelope, a design
description requires multiple processes in order to
prepare information for fabrication. Here models are
broken into functions that relate to the fabrication
one candidate design. Functional descriptions in-
corporate many areas of design and manufacturing.
Generated models are translated to descriptions
for fabrication, and then post processed based on
manufacture methods.
A fabrication description is implicit information taken
from a specific design description (figure 1). Fabri-
cation functions incorporate many areas of implicit
and explicit design starting with an unknown topo-
logical description. It is not always clear how best
to break building surfaces into parts from which an
assembly method will be defined. There are many
factors in subdividing a surface for fabrication. For
example, a model of an office tower is broken into
flat glass panels whose real size is based on avail-
ability in the market place. In design the divisions
can be based on available sizes of glass to be cut
on a milling machine. Functional descriptions also
include all issues associated with the manufacturing
of parts, from assembly description and method to
physical assembly procedures.
A fabrication function for creative design contains
four divisions of variable actions as identified in
figure 3. The function is applied to a divided surface
design. Next, constraints are assigned for each
panel of a divide surface(s) based on assemblies
and material of fabrication. Constraints can relate
to tolerances, material manipulations such as
bending and maximal or minimal sizes based on
material availability. Each constraint determines
(1) assembly design followed by (2) assembly test-
ing for quality and speed then (3) production parts
and (4) physical assembly. The four methods are a
process of fabrication used in the manufacture of
parts and final assembly of candidate designs (Lot-
ter, B, 1989).

Building Assemblies

A method to assemble a large model is described
here in four parts as these parts relate to the fabrica-
tion function above (figure 3). Assemblies are a criti-
cal component design in any product. The model in
figure 4a represents a ½ dome model divided into
parts for printing on an FDM 3D printer. The model
in figure 4b presents dome parts to be printed as
individual pieces in order to construct a model larger
than our 10“ square volume (12“ in height). Without
a method assembling this model alignment of parts
is hard to control and time to assemble is very high.
Model 4c is the same model build of parts allowing
for a glue-less assembly. Assembly design is a pro-
cess, and similar to any design process it is one of
trial and error. Criteria for each of the four section of
the assembly function are outlined here.

Designing Assemblies

Designing each assembly is a complex process of
organizing constraints to create part geometries.
Assemblies here are developed for the construction
of physical models on a table surface with parts
manufactured with rapid prototyping devices. The
control of part manufacture occurs in the computa-
tion, and there is little control over materials ma-
ipulation after the part has been produced. Post
processing was kept to minimum and control over
each part shape was managed within the virtual
world of CAD.
Methods of Design for Assembly should be simple and composed of as few parts as possible. Complex assemblies lead to complex manufacturing methods and possible confusion in translations between areas of the fabrication function. A basic method to design an assembly is outlined by Lotter who identifies rules for product design. The three most important points relevant to models built in this paper are:

1) The part should be divided into subdivisions of discernable stages.
2) Sub assemblies must be completed as a unit so that it can be handled as a single unit
3) Sub assemblies must be tested separately before adding to the whole.

Assemblies start with a base part from which other parts are assembled, and this base should be large enough to build off of. Next is assembly direction and ease of assembly where part orientation for connection depends on access to the locking mechanism of the previous part. The goal is to assemble parts by hand without additional tools. Second is that part orientation during assembly with simple mechanisms for screwing or snapping, by orienting the part direction when assembling is critical. All methods can be generalized within a computational description. This description can include descriptions beyond geometric into operational descriptions that are feature based or designed by key characteristics (Whitney, D E).

**Assembly testing and Design for assembly (DFA)**

Design for assembly is a process of designing components for and evaluating assembly quality by testing its function. There are many procedures for building assemblies based on the process of DFA. Robert Stone summarizes methods and presents techniques to apply DFA to a real assembly. The most important points are summarized here; there are two methods (Stone 2004). The first method of design for assembly was developed as a means to improve assembly ease and reduce assembly time during product production. Here the best adaptation of design for assembly is summarized by Redford and Chai in that they have defined four clear guidelines for assemblies: (1) the process should always include methods to improve design of assembly, (2) the design should be systematic, (3) the assembly process should be measurable and (4) should be friendly and of high quality. Most important is to reduce the number of parts in an assembly to simple, high quality representations (Redford, A, et al 1984). The second method developed by Boothroyd and Dewhurst defines the process of design and redesigning of the
existing design two or more times in order to create an assembly based on many evaluations. Each part is designed an initial representation, evaluated for function and visual design then redesigned (Boothroyd, G 1989).

An example of the DFA process is described using in figures xx – xx. Models generated in CAD are printed using an FDM 3D modeler then assembled and tested for strength and appearance. These models are test assemblies in preparation for fabrication of a larger dome (figure 6). The design constraints were strength in the physical model and natural light needing to penetrate the domes surface in the form of openings. Starting with a surface geometry of two crossing arches (figure 5a) the surface is divided into 1” segments (figure 5b). The obvious nature of the segmented parts demonstrates a need for assembly joints. The decision was made to divide the model into parts and FDM print each part as a flat shape, reducing the amount of support material, thus reducing manufacturing time.

The first model (figure 6) was created with many parts assuming that each flat segment of the arches geometry could be printed as a repeating unit. The joining member in between the flat parts would contain the angle that would allow the parts to create a curved shape when assembled. The quality of the final model proved to be weak and of too many manufactured parts. In order to strengthen the models assemblies, various tolerance tests would be needed until each part snapped together.

The second model was much more successful. It contained a male and female assembly mechanism and was robust enough to assemble without flexure. Each part was flat with the angled curvature built into the key. Once assembled, the sum of parts plus the key angle will form the double arch. The angle of the part was defined as part of the modeling process.

Design for Assembly is a process of generating test examples in search of increased design quality. Variations in quality are based on assembly function and translation from CAD representation to physical representation. In both modeled cases it was possible to build a curved shape of flat pieces with one piece or one area of the model embedded with a unique assembly.

**Manufacture of Models**

Once a part has been designed and tested it is ready for a low level manufacturing using a rapid prototyping device. These devices can fabricate many shapes in x, y and z coordinates. The work

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*Figure 5*

CAD descriptions of intersecting arches (left) description of original geometry, (right) division of arch surface into 1” length parts.

*Figure 6*

Intersecting arches built of two assembly geometries.
chose to limit the z motion to increase manufacturing productivity. The model in figure 8 demonstrates a method of (a) shape generation to start, (b) topological division and (c) subdivision, (d) assembly design and (e & f) production. Note that production trays contain pieces that are oriented flat in order to place as little support material as possible, leading to faster part production.

**Manual assembly of parts**
Final models were assembled quickly from embedded logic found within each part. Complications were found in parts with poor tolerance coordination. These parts did not fit tightly to opposing parts, making for weak connections and difficulties in the assembly of follow up parts (figure 9).

**Case studies of design assemblies**
There are two assembly study models presented here, and both are of the same generative process that translates 2D geometry to 3D Printing or 3D milling. Each contains aspects of the same issues to embed complex assembly knowledge within each manufactured component. Each component was designed to self-assemble upon contact.

**Embedded assembly rules**
The first example of a puzzle like wall assembly was constrained by assembly rules where each flat panel contained two dovetail connections. The flat panels in figure 10a contain a flat section and a section of dovetail like geometries. Flat panel geometry is generated using CAD scripting in visual basics where each panel is aligned vertically along a 2D curve. Between each panel are five dovetail shapes whose alignment is determined based on the variations in the curve. Each joined connection is unique and only assemblies to physically build one shape (figure 10). The script referred to as „Key Joint“ generates
Figure 10
Screen capture from generating model (a), arched parts with embedded structural rules (b) assembled model (c).

(a)  
(b)  
(c)

Figure 11
Line geometry (a), AutoCAD model in detail (b), manufacturing methods for struts and joint (11c), final assembled mode (d).

(a)  
(b)  
(c)  
(d)
a flat panel geometry perpendicular to the selected curve. Second, Key Joint builds dovetail assembly members also based on a perpendicular relationship with the selected curve.

**Milled Example**
Designing and building complex structures illuminates the need for the concept of self assembly, where all joints and members assemble on their own upon contact. Here a complex aggregate of structural nodes must assemble through embedded logic in order to fabricate a design study model seen in figure 11d. This model is an example of a large complex model built of joints and struts where no two members are of the same geometric description or are in the same plane of alignment. Starting with a line representation (11a) taken from points in space, struts and joints substitute (11b) for points. Parts definitions are (11c) prepared for the individual manufacture of joints using a small scale 3 axis milling machine. The final model (11d) was built with some glue, but most parts did self align and partially self assemble.

**Conclusions**
This paper has demonstrated that assemblies can facilitate the construction of candidate designs larger than the build volume for most RP devices. Through examples this paper presented methods of assembly and DFA based on the theory of a fabrication function. Each of the four parts of the function can be performed manually or computationally.

**Future Work**
Original geometry in figure 11a was taken from a generative program called EifForm. This program generates models through a rule based method, producing final models in the shape of dome assemblies. The model in figure 11 was not created through generative means. Future work will look closer at the concept of automating the generative nature of assemblies both in computation and physical assembly.

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