Fabrication of partially double-curved surfaces out of flat sheet material through a 3d puzzle approach

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Abstract

The topic of this paper is connection of digital modeling with generative programming and rapid prototyping, to produce physical sketch surface models. The physical surface models are assembled out of developable strips connected through a puzzle-like detail. The use of programming as a design approach allows the generation of connection details that corresponds to the rules of flat sheet rapid prototyping techniques of laser cutting and water jet cutting. With numerically controlled cutting there is no need to keep the joint detail related to manually achievable forms or to apply a standardized dimension. This paper demonstrates the possibilities of programming to generate cutting geometries that adapt to the local surface properties. The larger perspective of the research approach is the question of how to formulate and capture design intention through programming. What influence does the use of generative modeling in combination with rapid prototyping have on the design language of physical objects.

Figure 1. Example of puzzle joint surface

1 Introduction

Rapid prototyping and CNC machining tools are increasingly making their way, not only into production, but also into design schools. The machines are posing new challenges, not so much in their ability to execute drawings done on a CAD system by a process very similar to drawing, but by their ability to cut any geometry within the limitations of the machine. The question is how to expand the use of such machines and explore their potential. Two possible approaches are

- Extract the capabilities of the machine and embed them into a generative program that explores the possible forms and cuts within the limitations
- Design an object and adapt it to the machine's capabilities

There are always shapes for which a particular fabrication process works well and other shapes that need to be redesigned in order to be fabricated efficiently. As in conventional craft and manual production processes, there are "easy" and "hard" procedures in CNC. In this sense, CNC machines do not differ from the tools and processes involved in a conventional craft. What does differ is the potential for the creative reinvention of details originating in conventional craft in a CNC process. This can be accomplished through generative techniques where a customized solution for each detail is produced. However, few designers have explored these possibilities.

2 Fabrication and language of details

The language of a detail results from the combination of material, required performance, design intentions and its manufacturing process. If any of these parameters change, there is potential for a new detail to emerge. So far, few specific details have emerged from the use of computer controlled machining. This paper proposes an adaptable detail over a curved surface that would have been very hard to produce in any way other than through the combination of computer-controlled fabrication and generative modeling.

2.1 Tolerances, between pressure fit and constructability

The process of fabrication allows for the specification of very precise cutting dimensions. In the given example, the precision is crucial in order for the joint to be a pressure fit joint. But too high a precision in the fit will prevent the assembly of the joint: due to its spatial curvature, the continuous detail cannot be assembled all at once but only sequentially. The sequential assembly requires larger fitting tolerance to allow the pieces to move into place. The challenge is to find the right balance between a tight fit that would cause problems in the assembly, and a looser fit and that might cause the pressure fit joint to fail. Ideally this would have to be modeled into the geometry generation in the first place rather then to compensate for the variations through the cutting tolerances during fabrication.

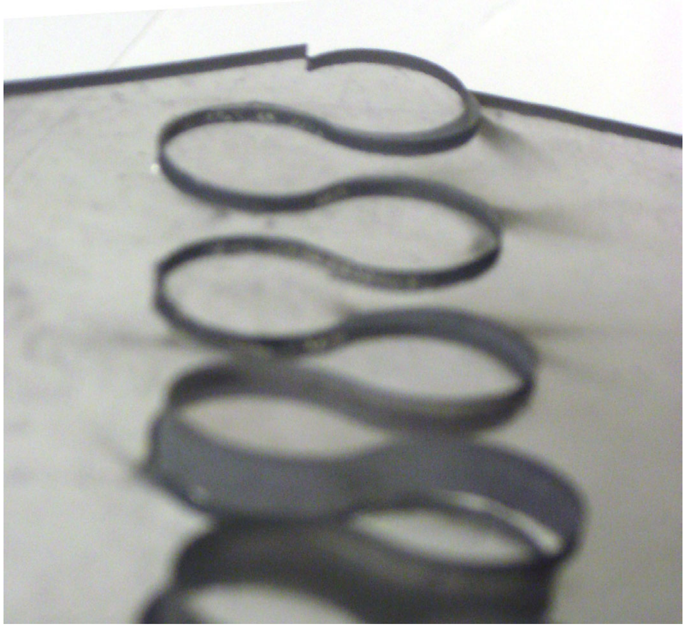

Figure 2. Balance between fitting tolerances and the constraints of assembly tolerances. The first nodes lock into place but prevent the following nodes to reach their position due to a fitting tolerance that is too tight.

2.2 Ability of details to adapt to their geometric context

A connection detail for a varying geometric context needs enough flexibility to work in the complete range of scenarios. Many experiments have been made, for instance in textile and membrane design, to come up with adaptable details to correspond to the geometric context. Assembly details in car design often depend on geometrically adaptable connections. For instance, a door seal follows the curved rail of the car body and the frame between the double-curved windshield and the car body describes a spatial curve. Such geometrically adaptable details are nothing new. What is novel though about the detail in this paper is that its geometric dimensions vary based on the context and are manufactured for that exact location. A further extension of this approach is to allow different variations of the detail during generation based on conditional checks of the local context. For instance if a curve becomes too extreme for one type of detail, a different type might be used.

Figure 3. Depending on local context the detail's scale and orientation changes.

2.3 Changes in standardization

With the generation of geometry through scripts that allow for parameter-based variations, the notion of standardization shifts from dimension based descriptions to a topologic system of relations. It is no longer necessary to fix a certain dimension at the interface between components, but the relationship of the two parts defines the shared dimension. The standard shifts to the description of the relationship. It is important to know how elements relate to each other, but it is not necessary to know their absolute dimensions. Parametric modeling has set the stage for the expression of elements as a set of relations that have variable dimensions. A non-dimensional based standard relies heavily on fabrication techniques that allow for the production of varying geometries based on a system, as in the example of the joint shown here. Generative approaches through programming allow the generation of complete systems out of a set of rules. Robert Aish, Director of Research at Bentley System has developed a very promising approach to programming integrated into parametric modeling systems in the Custom Objects extension to Microstation.

2.4 Importance of material modeling in the design process

The example of the 3d puzzled surface shows the importance of material simulation for the design process. Material behavior should be captured in correspondence to the geometric distortions. In the example, the material is not simulated. The distortion of the strips causes the dimensions of the pieces to change, which affects the relationship of the parts to each other. This in turn affects the assembly process. Without simulation or anticipation of the material response any digital geometric model is just a representation of the desired form. It lacks the information how to manufacture it correctly. The shortcoming of the puzzle surface demonstrates that clearly. The majority of the geometries produced develop problems during the assembly process due to the lack of material simulation in the generation process. Simplified techniques of embedding material properties are for instance constraining models to planar or to developable surfaces. Dennis Shelden, Director of Computing at Frank Gehry's office has developed different tools and techniques using this approach as well as the modeling of material properties of paper. "Parametric technology allows relationships among geometric elements to be encoded in the model as part of operations on these elements."(Shelden 2002)

2.5 Self-registering geometries

When using manufacturing techniques that require post-fabrication assembly, it is very helpful to have self-registering geometries that allow for exact alignment of pieces in space. The puzzle joint is one approach to this problem. The continuous curvature of the joint provides a continuous fit between parts. In addition, it allows, in most cases, for only one, unique assembly of the pieces. In order for the pieces to snap together, they have to take on the desired 3-dimensional shape. This ensures proper alignment of the pieces and the approximate three–dimensional shape of the overall form. However, inaccuracies result from the transformation of the digital geometry into the physical representation, as the current digital models do not take into account material properties, as for instance resistance to bending and material stiffness. When, in the case of the joint, one node forces a partial buckling of the surface, it affects the neighboring nodes as well. In the worst case, the propagation of these deformations renders the assembly of the pieces impossible.

2.6 Finite element analysis study of a joint sketch model

The author has done a draft analysis of the joint properties in the finite element analysis workbench of the CAD program CATIA. The results shown here are very preliminary and are shown only to illustrate the general properties of the joint behavior in terms of qualitative stress distribution and points of high and low friction. The friction distribution is particularly interesting, as friction is essential in making the joint work. The joint simulation was done with a 0.01 mm pressure fit overlap between the contact surfaces of the two test pieces. Friction is highest at the tips of the nodes, where the displacement tends to be the highest.

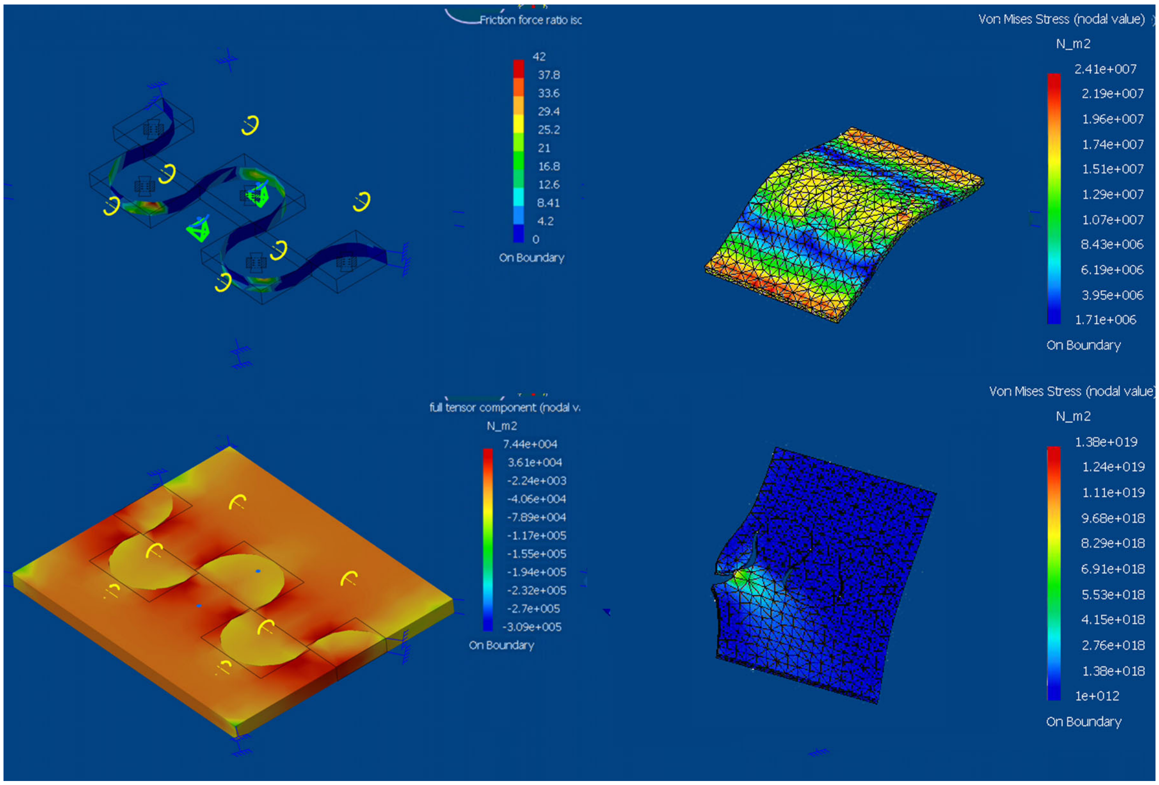

Figure 4. Finite element analysis studies of the joint properties (the studies are very preliminary and not representative of accurate force distributions.

2.7 Extending the approach to 3d printing

The approach of writing code can be extended to other prototyping machines, such as 3d printers and milling machines. It is important to capture the machine's properties. The generating code for the fabrication process should make optimal use of the machine's properties, while staying as close as possible to the actual geometry of the piece. Each technique requires a particular type of detailing to respond to the requirements of the chosen techniques. For instance, material thickness does not scale well. A cardboard sheet cut at the correct model scale on a laser cutter might be too thin to work in a friction joint. Or a 3d print at the correct proportion might break due to the brittleness of the print material. The joint example in this paper was initially developed in 1999 when the author witnessed the purchase of a laser cutter and attempted to explore the potential of computer-controlled cutting. The process was explicitly developed in response to the machine to provide for rapid production of physical sketch models from three-dimensional surface models. A similar approach was taken for the 3d printing process as illustrated with the space frame example. Recent work has explored the connection of scripting and 3d printing in depth. "This exploration has been guided by an intention to design physical objects through procedural programming."(Loukissas 2003)

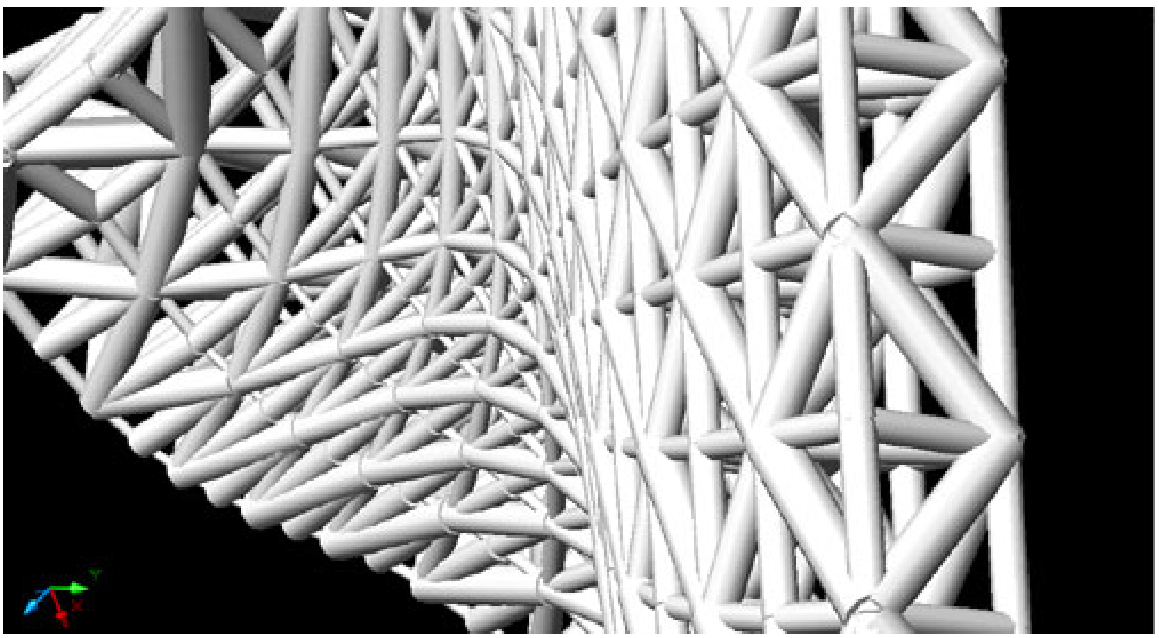

Figure 5. The same script used for surface generation can also generate a solid space frame over the spline surface that can be 3d printed on rapid prototyping machines.

2.8 Issues of scale

As rapid prototyping machines have limited bed sizes, the question of assembly is important, especially in an educational context. The ability to build larger, cheap prototypes out of pieces with a limited size requires connection joints that can be put together without additional hardware. The linear puzzle joints helps in connecting surface-based materials in a planar fashion. It establishes a tension and compression connection as long as the joint stays within the plane of the surface connection. This connection is achieved through pressure fitting the parts and does not require additional fasteners. Exceptions are materials where the material thickness is too thin to provide a pressure fit connection. For this condition a flexible rubber seal was used to allow for a continuous connection, for instance between aluminum sheets. This seal could also act as a preliminary water barrier in providing a continuous surface seal.

2.9 Shift of the design focus from geometry toward building systems expressed through generative or parametric systems

Increasingly, the introduction of digital-based modeling will shift the focus of design away from fixed geometry towards parametric or generative constructs capable of producing a variety of geometric output. The important difference is that parametric and generative models can be set up to contain fabrication constraints and material properties that allow for the exploration of form within these constraints.

3 Description of the process of fabrication

The following describes the process of producing a puzzle-jointed surface through an application written in Autolisp within AutoCAD. The process has been developed since spring 1999.

3.1 The surface

A surface is modeled with the help of a custom-written quadratic spline surface modeler in Autocad using an Autolisp script. The surface is defined through eight slopes, two each at the surface corner points. The slopes define the incoming and outgoing slope of the surface edges of the spline surface. The spline surface is adjustable in its grid cell resolution through a custom command. The grid cell resolution determines how close the surface approximates the numerical spline surface and is the basis for the generation of the puzzle joint detail as well.

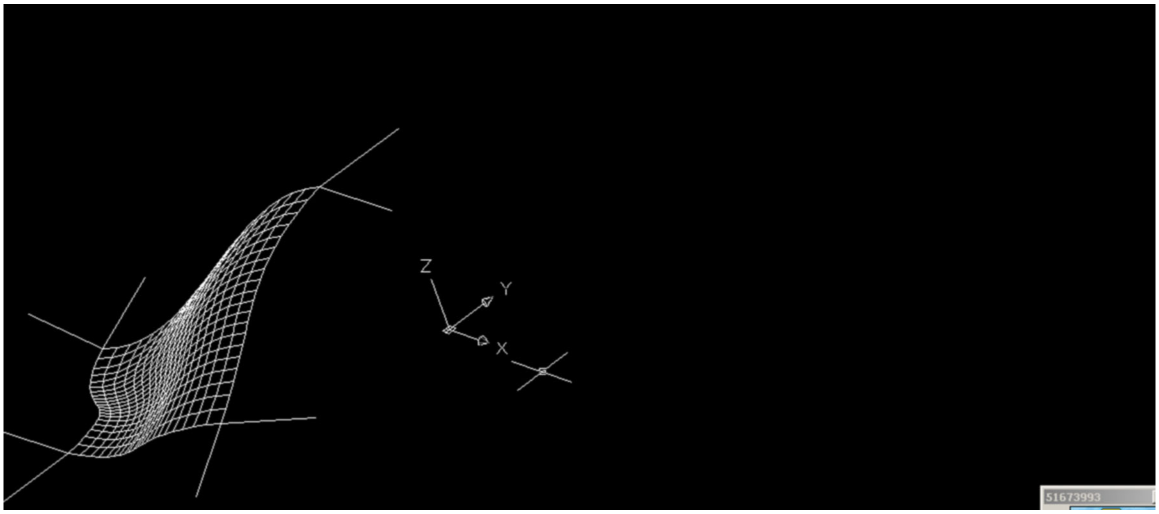

Figure 6. The spline surface, as generated in Autocad by the script. Its grid resolution is set to 20x20 cells.)

3.2 The strips

Once the desired form and resolution is achieved one can use another custom command to develop the strips in one of the UV directions of the surface as strips onto the ground plane. The process uses a crude triangulation technique, but since the topology of the surface elements to be flattened is known and each strip has only one neighboring strip with one shared edge, this approximation is not a problem. The flattening technique also ensures that there are no overlaps between the parts when they are flattened. Once the parts are flattened, the joint detail is generated based on the resolution of the surface strip. The variation of the edge line spacing is based on the overall grid resolution of the initial surface.

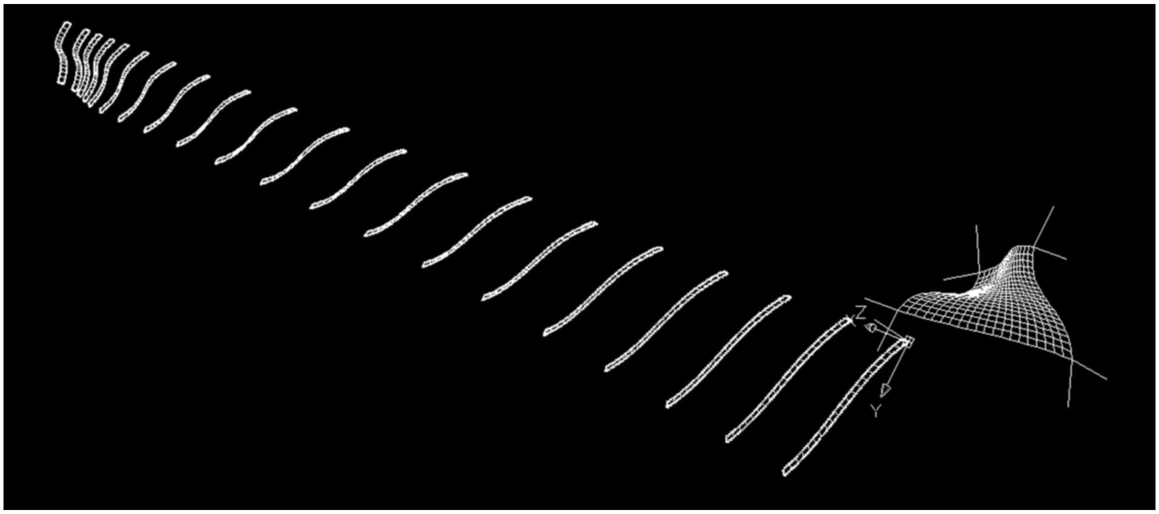

Figure 7. After running the fabrication script over the surface 20 strips are flattened out

3.3 The joint

Once the cutting line layout is generated, the testing begins to fine-tune the balance between cutting tolerance, material thickness, material stiffness, and the friction of the faces of the cut. This balance influences how well the joint will pressure fit. Since the pieces are curved, the assembly can only be done one joint at a time. The offset introduced through the curvature is much larger then in a planar configuration. The joint has to have enough play to be assembled. But if the tolerance is too great, the joint will not stay connected through the material friction. The actual joint geometry was born out of the quest for a geometry that would allow for fastener free surface connections, which would be able to transfer forces within the surface, both in tension and in compression.

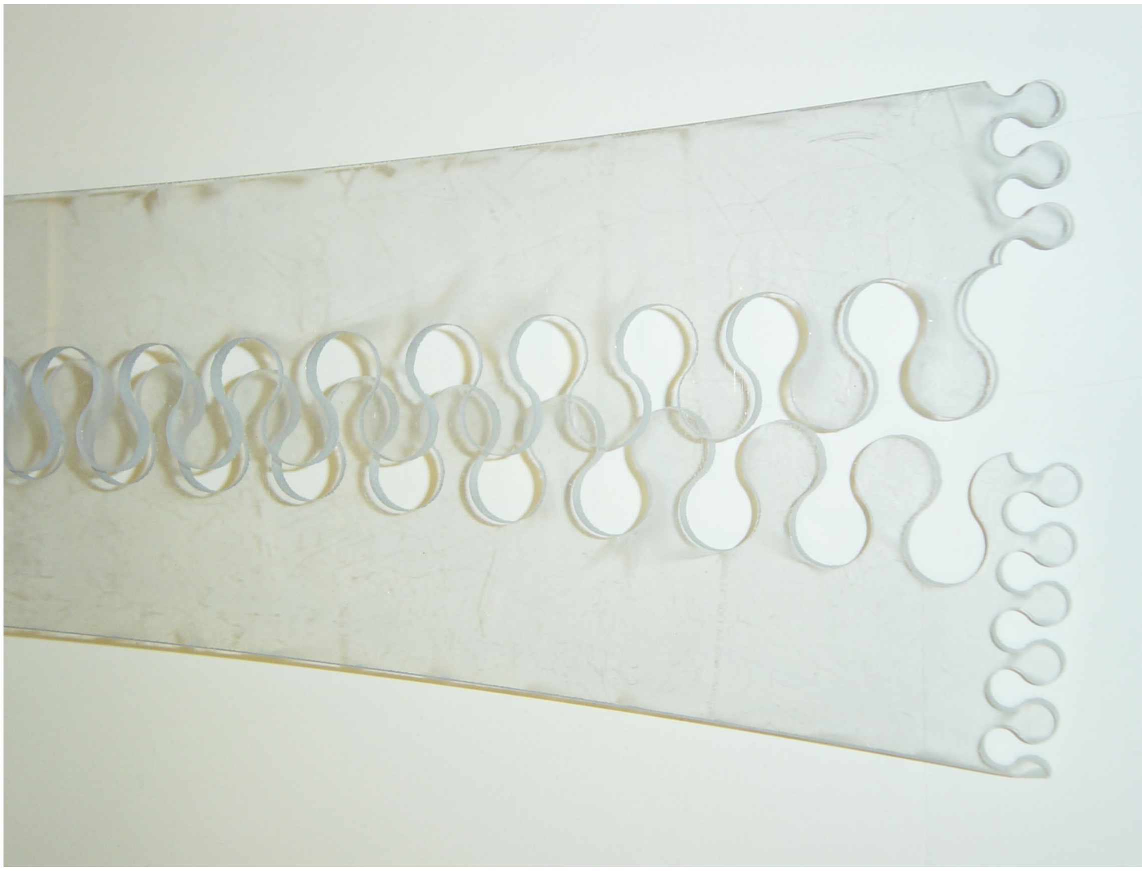

Figure 8. A testing strip made of polycarbonate clearly showing the joint properties

3.4 The material

For various materials, iterations of test joints with different cutting tolerances were made. Tested materials were polycarbonate, aluminum, various cardboard types, wood and Plexiglas.

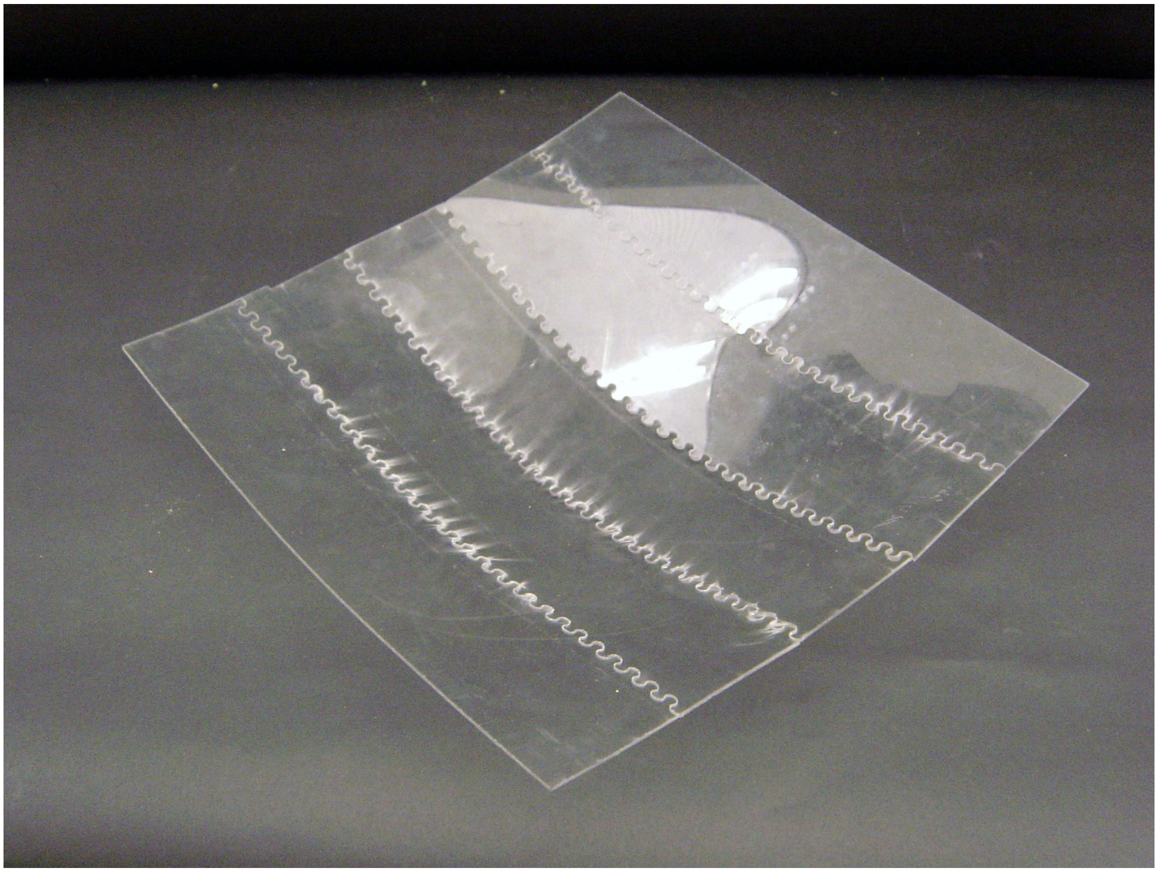

Figure 9. A polycarbonate surface example

3.5 The cutting

Once the tolerances for the cutting process are established, the layout is cut either with a laser cutter or a water jet cutter, depending on the material. Most cardboard and wood materials could be cut with the laser cutter, whereas polycarbonate and aluminum were cut on the water jet cutter. Once the pieces are cut, they are assembled. Curvature is applied along the lines of ruling. A rubber hammer is used to pound the joints into places. This is necessary in order to overcome the friction in the joints that hold the pieces in place.

The polycarbonate piece has been the most successful in terms of assembly and strength after the assembly process. For the polycarbonate sheet, a special cutting technique was applied. Every other strip was mirrored before cutting, in order to use the valley shaped blasting crater of the water jet cutting process to the advantage of the joints. Through mirroring the cutting line of every other strip, the surfaces of the cutting edges lie parallel and greatly increase the friction between them.

Figure 10. Cutting of the polycarbonate pieces in an OMAX™ water jet cutter

3.6 Side effects of the puzzle joint

Since the puzzle joint does span over the edge-line of the developable surface strip, it is geometrically not a clean component. It is attached to one strip with single curvature, but through the joint properties it is forced to lie within the surface of the neighboring strip, which does not share the same curvature. It therefore takes on a partial double curvature. This actually helps the pieces to approximate the numerically double curved surface the strip approximation is based on. But the process is very uncontrolled and hard to predict. In many cases it fails, and the bending force pulling the puzzle node out of its position is greater then the friction force keeping it in place. However, the process also has positive effects. The joints are pre-stressed which increases the friction in the joints through the increased forces acting on the joint seam.

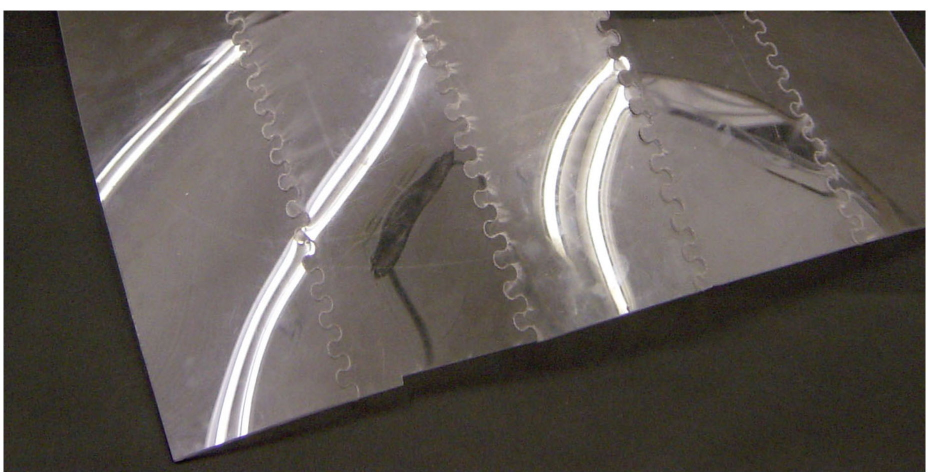

Figure 11. Reflection lines show the distortion of the developable strips into partial double curvature due to the joints bridging the ridge between the strips.

3.7 Layout of the surface patches that use the puzzle joint

The basis for the puzzle joint is the geometry of the actual puzzle pieces. In the demonstrated approach, the chosen form is that of a developable surface strip. The spline surface is divided up based on the isopram UV lines at regular intervals. This guarantees a certain correspondence between surface properties and strip properties. But it does not take into account the difference in curvature between neighboring strips. A more promising approach would be the use of a tiling scheme that analyses the local curvature condition and orients the seams in the optimal orientation to the slope of the surface. A study was done by the author using Genetic Algorithms for the description of finite state automata that would walk across the surface reacting to the local curvature. It is a relatively complicated interconnected model that does not allow for very reliable results due to the number of parameters that can be adjusted. The main challenge is to define a reliable fitness function for selection of the FSA for the strip production that does allow for new patterns to emerge but does not limit the selection too closely.

4 Conclusions

The larger perspective of the research approach is the question how to formulate and capture design intention through programming, and what influence the use of generative modeling in combination with rapid prototyping has on the design language of physical objects. The author predicts changes in the language of details by generating details that adapt to local geometric and material properties through programming. The designer writes programs as part of the overall design. Code will be written that adapts a design for a particular fabrication method and incorporates machine-specific properties into the design. There is a general distinction between rapid prototyping for the means of production and large-scale fabrication, rapid prototyping for representational purposes for studying the form, and rapid prototyping as a design exploration tool. As a design exploration tool it allows the designer to generate large number of iterations of physical models that are representational, but are also studies of the assembly process, material properties and fabrication sequences.

The goal of this exercise in the long run, is the integration of the material properties as well as the methods of fabrication into the generation of geometric representation. In the best case an integrated design cycle takes full advantage of the possibilities of the digital medium and the computer controlled tools.

5 References

Aish, R. (2000) Custom Objects: a Model Oriented End-User Programming Environment. draft paper submitted to the Visual End User Workshop VL2000

Loukissas, Y. (2003). Rulebuilding, Exploring Design Worlds through End-User Programming. SMArchS thesis, Department of Architecture, Massachusetts Institute of Technology, Cambridge, MA.

Shelden, D. R.(2002). Digital Surface Representation and the Constructibility of Gehry's Architecture. Ph.D. thesis in Department of Architecture, Massachusetts Institute of Technology, Cambridge MA.