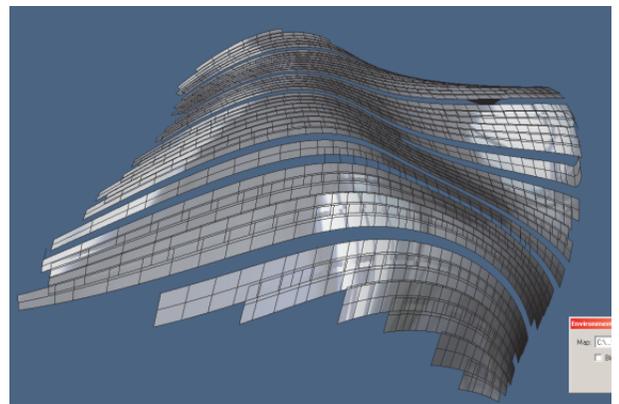


## **6.836 Embodied Intelligence**

### **Final Project - Axel Kilian**

#### **Using Genetic Algorithms To Generate Developable Strips From Free formed Surfaces**



## Problem description

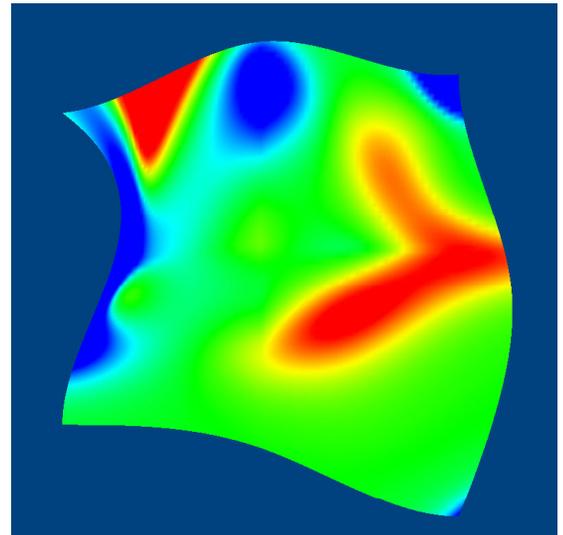
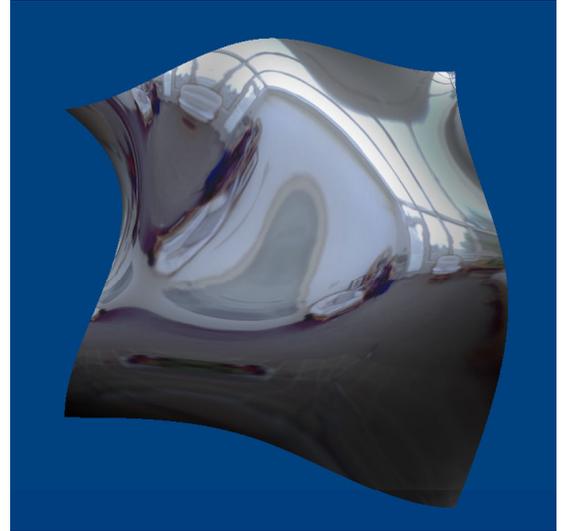
In Architecture there has been an increase in the use of free formed surfaces partially through the availability of advanced surface modelers for moderate prices and partially through pioneers like Frank O. Gehry who have pushed the constructability of free form surface geometry into large scale construction.

Surface types that are mainly used are NURBS surfaces which are Non Uniform Rational B-Splines. They allow for continuous curvature modeling without the need to work with meshes or even triangulated surface polygons. This makes the surface representation very powerful but at the same time it introduces a fundamental problem of constructability. NURBS surfaces have been used in aeronautical, ocean and automotive engineering for years and in all these sectors techniques for translating the double curved surfaces into build form have been developed. Stamping the most widely used process for large volume production is the most powerful technique for producing pieces with very close fit to the original geometry. Due to the nature of Architecture being mostly small series or even more often one of a kind buildings the big series techniques like stamping are not applicable for projects with a somewhat normal budget (there have been exceptions for instance the DG-Bank in Berlin built by Gehry's office and Schlaich engineers) Therefore other techniques are required to approximate double curved surfaces.

One approach is to analyse the surface regarding curvature. The images on the right depict two ways of doing so.

The first shows a visual inspection method using the a mirror technique and an environment map, in this case the image of a sunlit room. The reflection of the image on the surface allows one to visually judge curvature and continuity of curvature. This is mostly a qualitative method that does not give absolute results but helps designers to get a feel for the type of surface they are dealing with.

The second image shows the same surface with a coloring technique that shows mean Gaussian curvature. The areas in red show areas of high mean Gaussian curvature the green and blue areas are less. This is once more a way for Designers to understand the surface properties and to think about appropriate approaches for making them constructable.



## The strip approach

This approach requires to divide up the surface along curves that ride on the original surface (where possible) and to loft adjacent surface curves. Lofting means to connect corresponding points on each of the curves with straight lines of ruling and thereby effectively eliminating curvature in one direction. This leaves the resulting stripes in the desired case with curvature only in one direction which makes the strip under certain conditions developable. Developability means the strip can be developed onto a planar surface without triangulation.

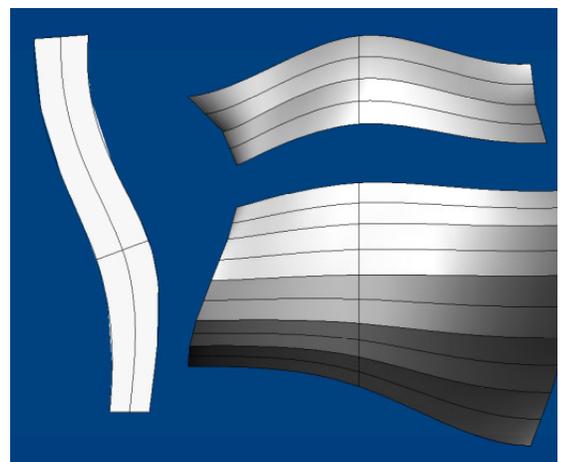
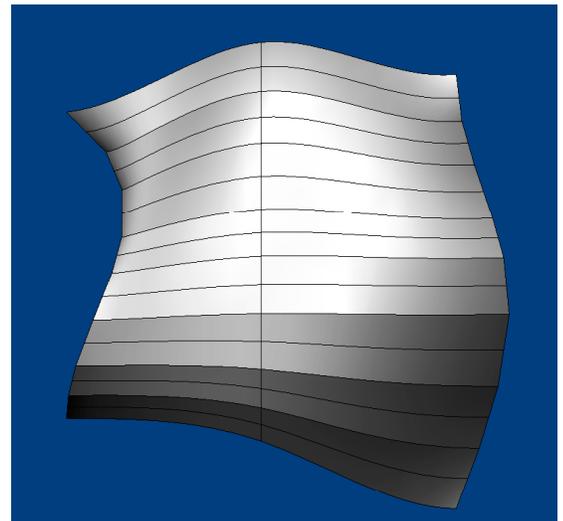
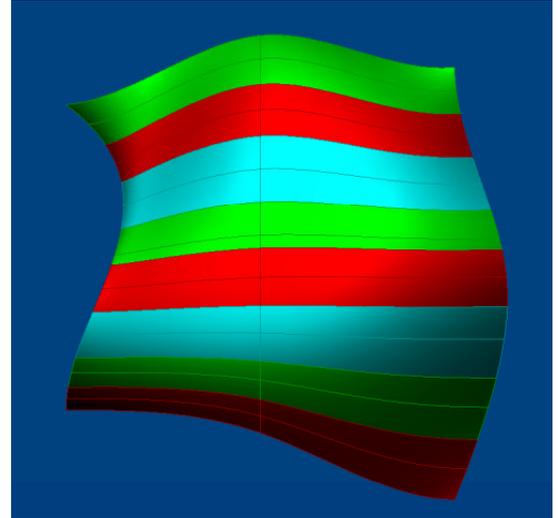
The images on the right show the steps in a very ideal and general situation that does hardly ever occur like this.

The first image is the original surface split up along the isoparam lines with arbitrary spacings in between, still keeping the double curvature. In the next step the curves have been lofted and the original surface replaced with the lofted strips. In comparing the two images one can get a sense for what the issues are in choosing the spacing and direction of the strips on the original surface. In this example no consideration in particular was given to whether the resulting strips would be developable. It is possible that the resultant strips would not be developable due to their geometry. The definition for developability follows in the next part.

Choosing the strips and placing them is a difficult problem since the geometric conditions are hard to predict

## Developing the strips

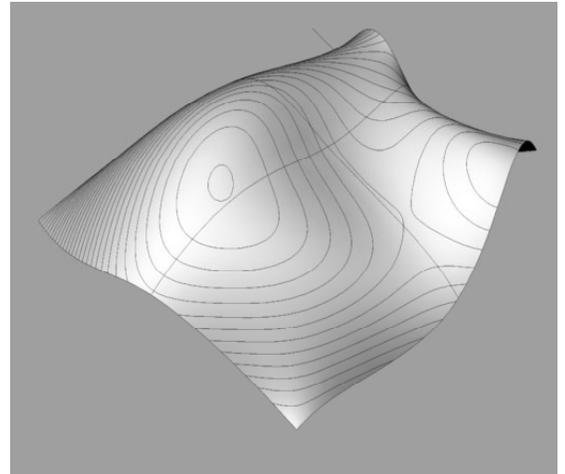
The lofted stripes can in most cases be developed onto a plane. This is important because it allows for the use of sheet material like sheet metal or wood in standard panels without the need for expensive stamp forming or steaming processes. If the thickness of the material is thin in relation to the surface it covers it is usually unproblematic to bend it in the one curvature direction.



## Alternatives to Isopram subdivisions

An alternative technique often used is sectioning of the surface with parallel offset planes. This produces a set of contour lines depending on the orientation of the planes to the surface. This can in certain orientations produce interesting subdivision patterns but does usually not work well as a developable transformation

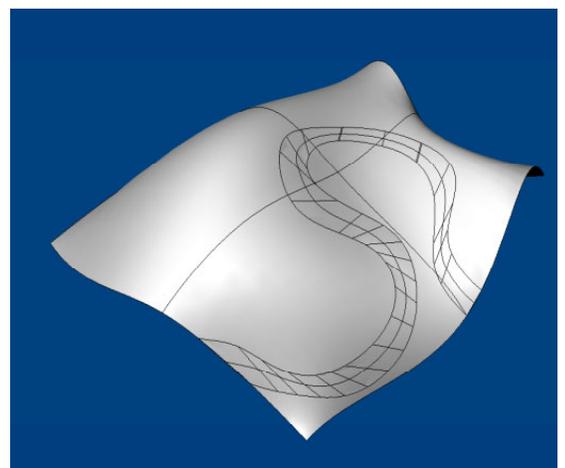
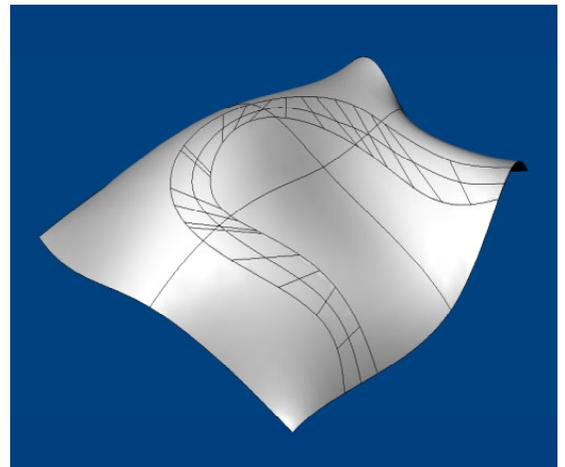
The alternative chosen for this project is a harder one. It is to place strips onto the surface and have their path be determined by the surface features like curvature, and surface normals.



The two examples below give an impression of the desired outcome, whereas the shown example does not fulfill the criteria of being developable since the lines of ruling do not have normals that lie on the same plane.

The task of this paper is to use a GA setup to evolve creatures that find strips based on the surface features that fulfill the developability constraint. This is very hard to do by hand and therefore it seems very suited to evolve different individuals with different approaches and choose the best ones.

The fitness parameter is a difficult one since there will be few strips that conform perfectly to the original surface. It is also not necessary to achieve a perfect fit since the materials used like metal and wood for instance have a certain tolerance for double curvature or buckling to compensate for any slight offsets.

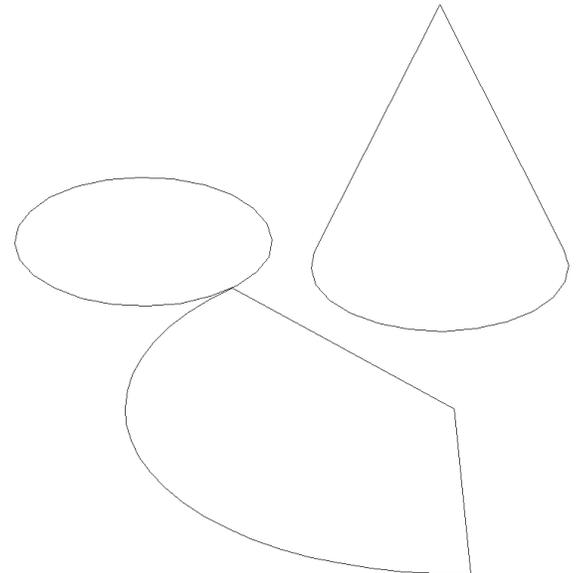
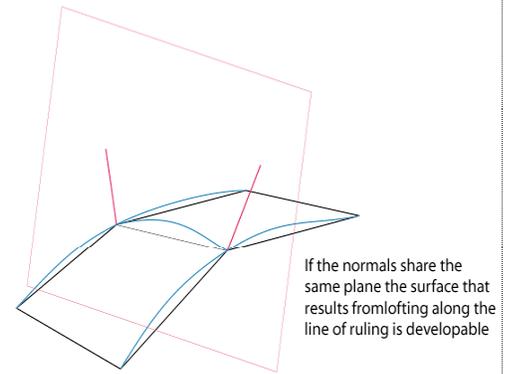


## Developability

In order for a strip with one dimensional curvature to be developable according to research done by Dennis Shelden, head of computing at FOGA, it is necessary that the normals at the two ends of a line of ruling share the same plane. This condition requires the surface tangent to be on the same plane as well but does not require the same curvature in each point. For instance a cone is a developable surface since its normals along a line of ruling on its cone surface share the same plane and at the same time the curvature at the top is stronger then at the base.

Developability plays an important role in production and manufacturing of parts that are sheet material based. In order to get a surface that is crinkle free the developable constraint has to be met. An example of a condition where developability was not met is the Bilbao Guggenheim Museum by Frank Gehry. The Titanium skin is made of individual sheets that overlap like the scales of a fish. The metal does not perfectly conform to its substructure though which required some forcing of the metal into place. This slight departure of one dimensional curvature causes crinkling that is mainly visible in the reflection of the sheet metal.

In the case of the museum the effect was tolerated and even aesthetically desired by the architect. In future buildings it was prevented as the building and skin systems evolved further.



Developed cone showing a developable surface with varying curvature depending on the position on the height of the cone

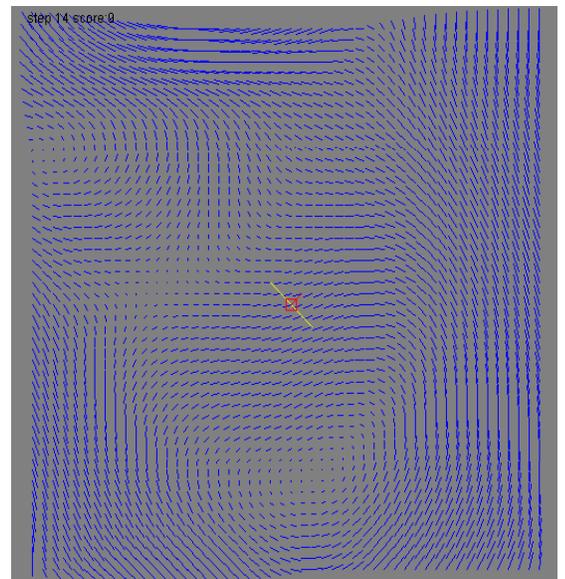
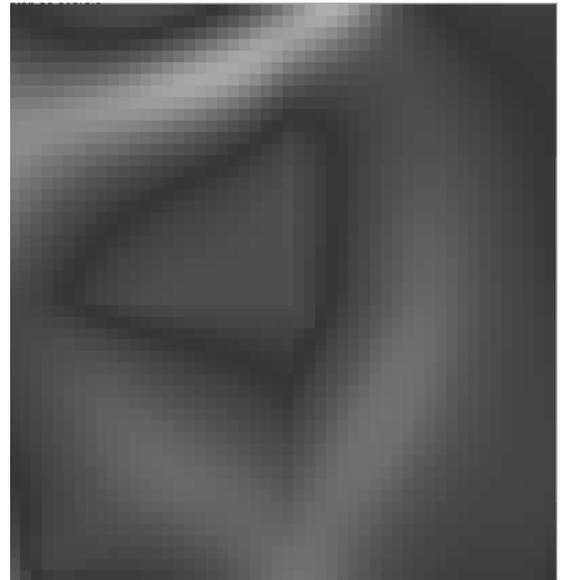
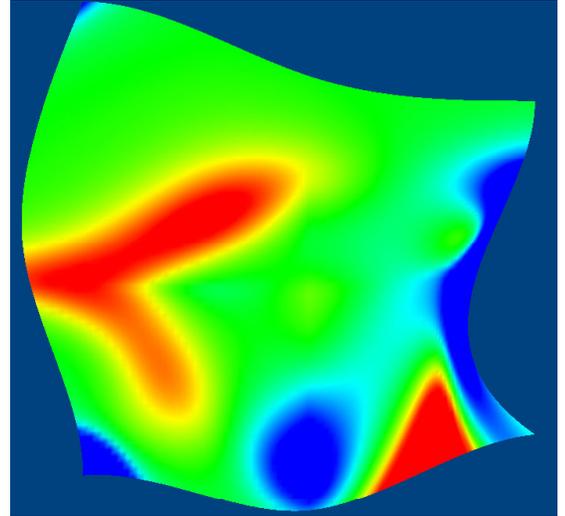
## The environment

The environment for the GA model is the UV space of a NURBS surface. The UV space is the two dimensional representation of the three dimensional surface on a flat plane with width and length dimensions corresponding to the degrees of the surface. This gives the possibility to operate in a rectangular two dimensional environment which is easier to deal with and still maps perfectly onto the original three dimensional surface.

The features of the surface are represented through the normals that are mapped onto the environment. The curvature comes into the environment through a mapping of the grid cells onto the surface.

For the environment a resolution of 50x50 grid cells derived from sampling mean Gaussian curvature and normals at 50 equidistant divisions along uv space of the NURBS surface.

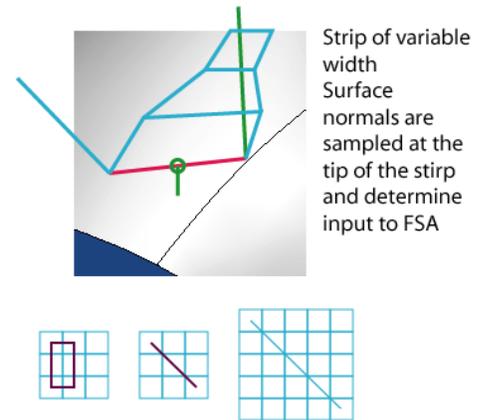
This allows for faster processing and accessing of the surface information in the running of the GA. It reduces accuracy though since the sampling is relatively rough. But for now this model has been chosen but there are possibly higher resolution that would work better for the problem at hand



## The strip creature

The bases for the phenotype that is defined by the genotype of the GA is a so called "strip-creature" or ant that runs along the UV space and has two normal sensors placed at the tips of its line of ruling that is orthogonal to its direction of movement.

The creature can move, turn and widen and narrow its strip based on the FSA and the input of the environment. The goal of the creature is to travel along the surface leaving a strip trail where each normal pair at the lines of ruling is sharing a plane. If this condition is consistently met within some tolerance margin the strip that results is developable.



## The FSA

The behavior of the creature is based on a FSA representation. The possible actions within the FSA are move, turn left, turn right, do nothing, widen the strip, narrow the strip. With the chosen binary representation in the genome a three bit representation for the action is chosen which results in 3 neutral actions in order to fill all possible states of the three bits.

The number of possible states varies with different experiments between  $2^3$  and  $2^4$  states. Hand designed test FSA did seldom go beyond 5 states but in order to give the system enough flexibility to evolve the number of possible states is set intentionally higher.

## The genome

The genome is using bit representation that means the least significant bit is on the right and the most significant bit on the left. It is divided into segments where each segment represents either a state or an action related to that state. (similar to the ants assignment in the research assignment no.4)

The genome is represented as a string of bits

`000010011001001.....`

Where the bits are assigned the following meanings

Start state	new state	action	new state	action
000	010	011	001	001

This can be expanded to a transition table

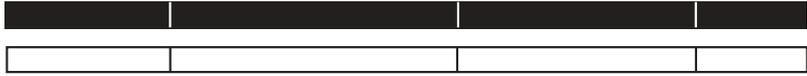
start state	old state	input	new state	action
000	001	0	010	011
	001	1	111	010
	010	0	011	010
	010	1	111	010
	011	0	011	010
	011	1	111	100

....



solution by mutation from generation to generation.

### The evolution process using point mutation and crossover



Mutation of the genome is taking place after all individuals of a generation have been run on the surface and their scores have been recorded. The top 10% of the individuals in terms of scores are stored and subjected to point mutation and crossover .

The probability for point mutation is 1% per bit in the current implementation. Different probabilities can be set to increase the likelihood of mutations.

The initial crossover was a three point crossover, in the later runs it was changed to be one crossover. At three randomly picked points in the genome each of a randomly picked genome is split. The resulting pieces are swapped and combined with their counterparts from the other genome and two new genome result from it.

Point mutation simply picks a single Bit and flips it based on a variable probability.

The resulting mutated genomes are inserted into a new population of randomly generated genomes. This is an important part of the evolutionary process to allow new variations into the gene pool. If the evolution would only be run with the selected top 10% of the genomes there would be stagnation in the long run.

For this paper runs with both point mutation and crossover were done as well as runs with point mutation only for comparison. The results are reported in the data section.

## The resulting strips

After running the GA for a total of 1000 individuals for 200 generations using 1% probability of point mutation and 3 point crossover. A range of strips could be observed first of all not based on scores alone but rather gathered visually by different types.

The stripes are the result of 1000 steps of the creature on a 50x50 grid.

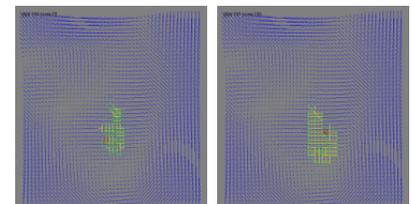
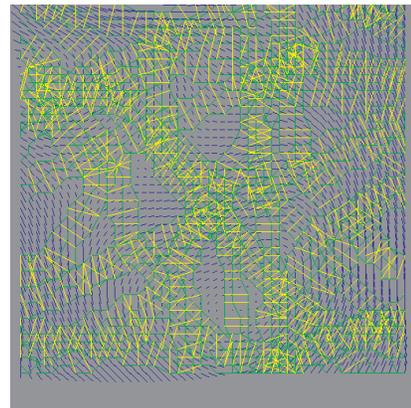
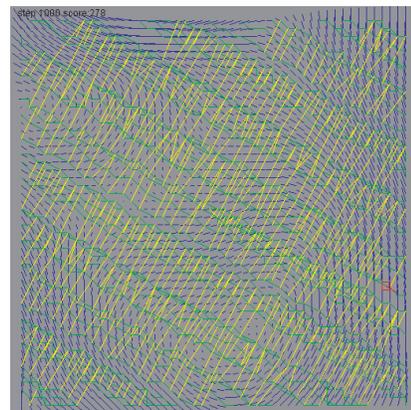
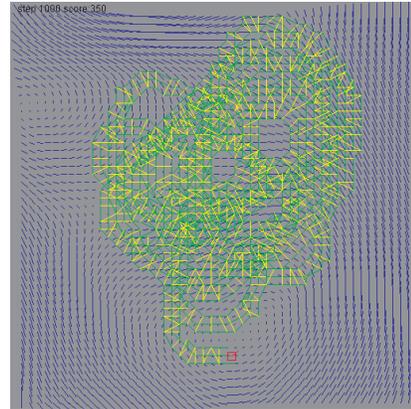
A common phenotype was a centrally located patch formed by the strip running in circles around it wrapping back onto itself.

Another type was the diagonal pattern with strip dividing up the uv space in more or less parallel strip patterns. This type must be relatively isolated from the surface feature inputs in order to run straight for such a long time. Since the surface is

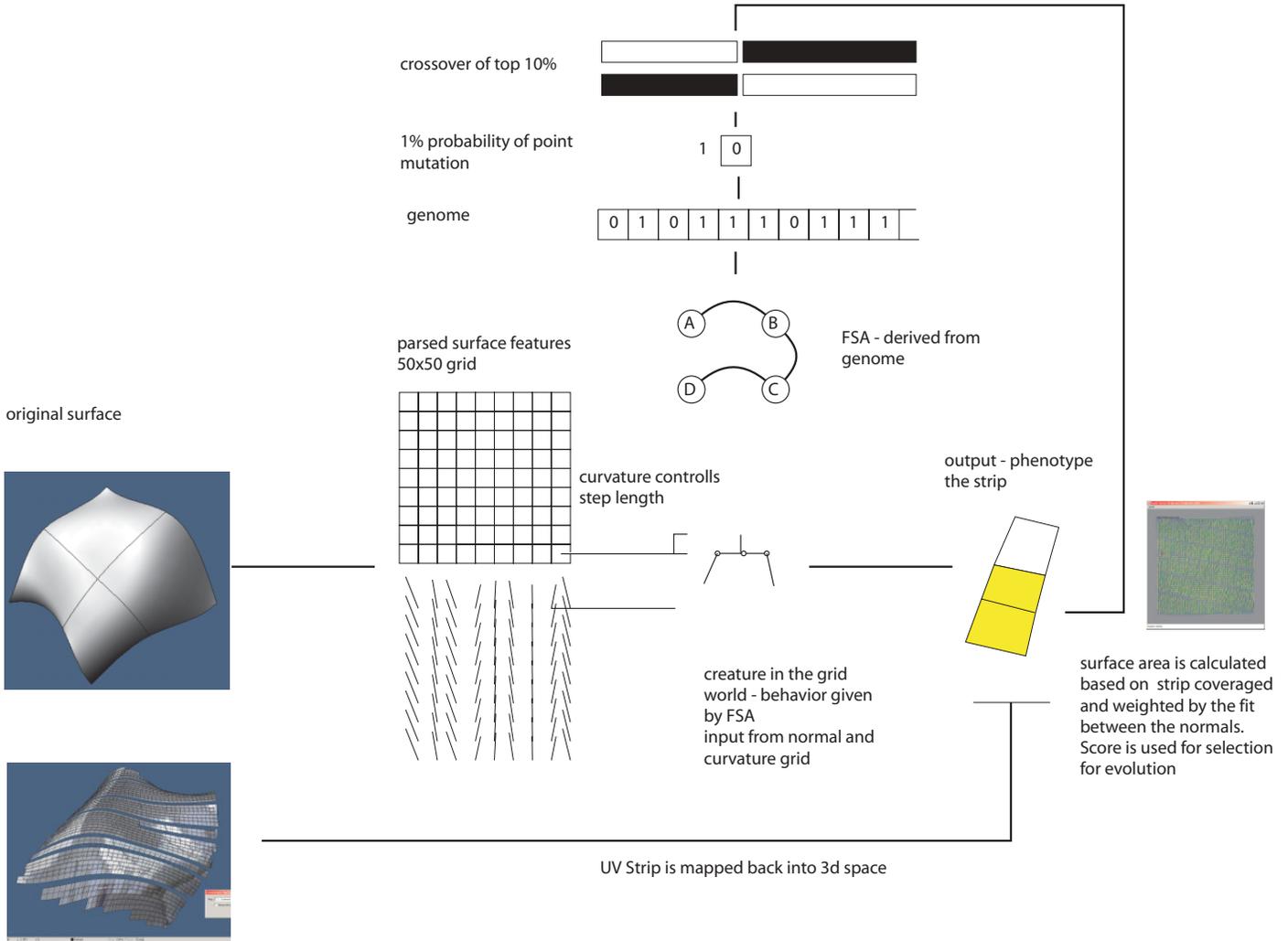
Being treated toroidal the surface can be covered with one strip that wraps around itself.

The crisscross pattern. The strip conforms to the surface features and follows ridges and folds and based on the toroidal surface model cuts across the UV plane from different angles. This is the most desired output - although it is very chaotic it does open up the opportunity of a new Approach to subdividing the NURBS surfaces with unconventional strip patterns that would be hard to conceive otherwise.

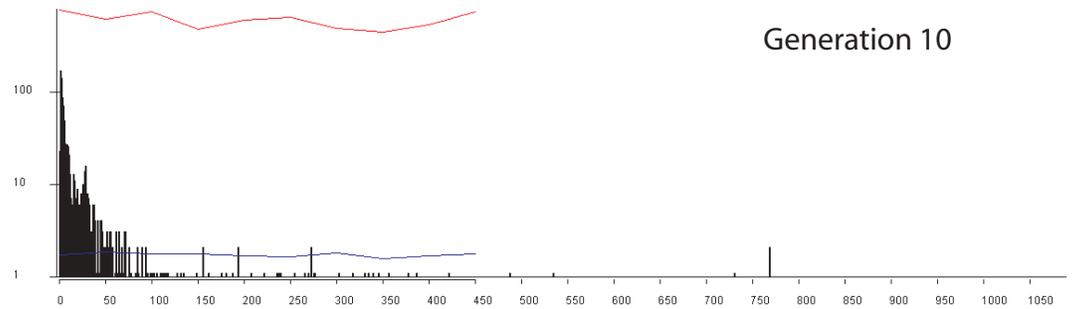
Images from an earlier implementation where the movement of the creature was still limited to 90 degree turns only and four neighbors



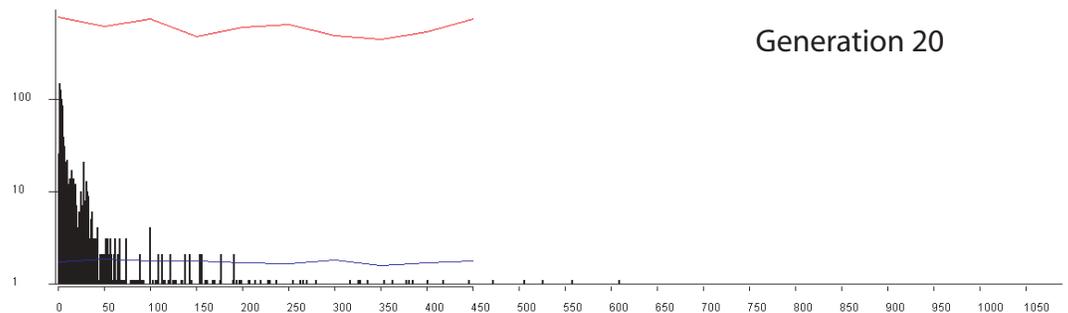
# The process



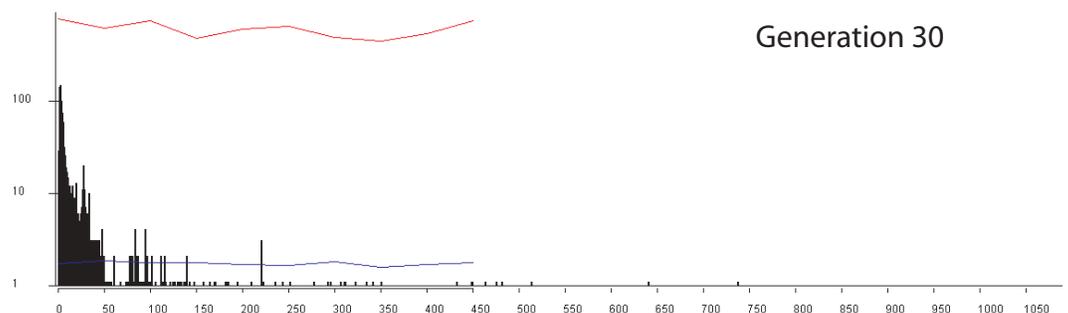
## Initial Data

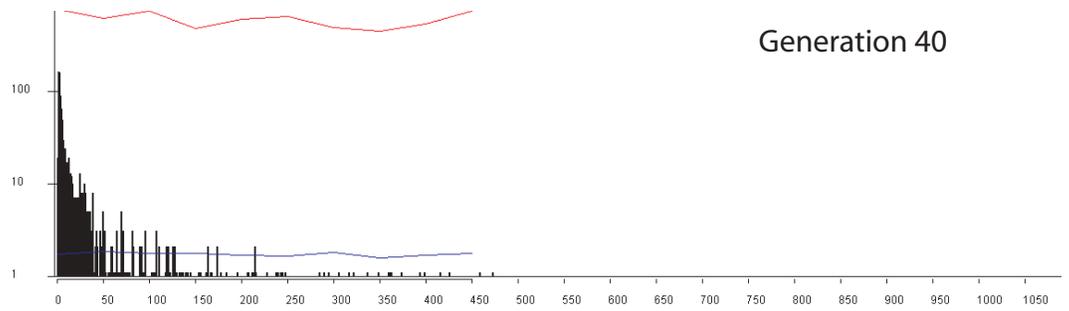


Graphs depicting the development of a population of 1000 strip individuals over the course of 200 generations. Each bar represents the amount of individuals with the same score in one generation. The lower curve is the mean score across a generation on the y-axis and on the x axis it is marked for each generation to show the development over the course of evolution. The x axis is a log10 algorithmic scale axis. The top curve is the highest scoring individual of each generation.

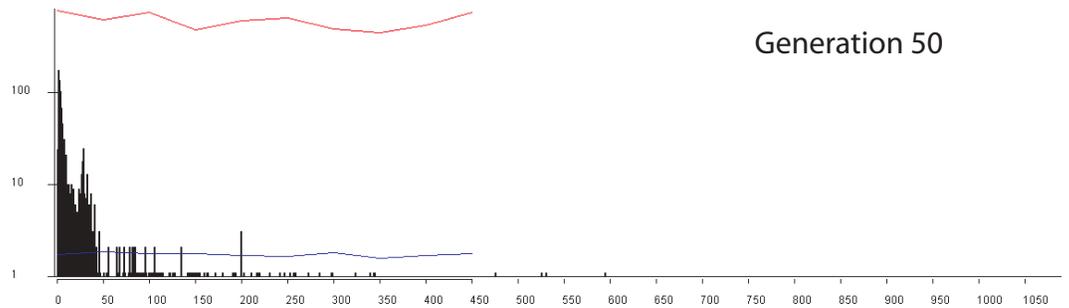


The graphs show jumps in generation of size 10 with the last slide showing generation 200. The number of generation and population are still far too small to show significant improvements through evolutionary principles but particularly high scoring individuals occur over the course of the generations and vary through mutations. Overall there is no significant increase in the overall performance of the set of individuals based on the particular fitness function used, which is in part a problem of evaluating the outcome of the strips. The overwhelming

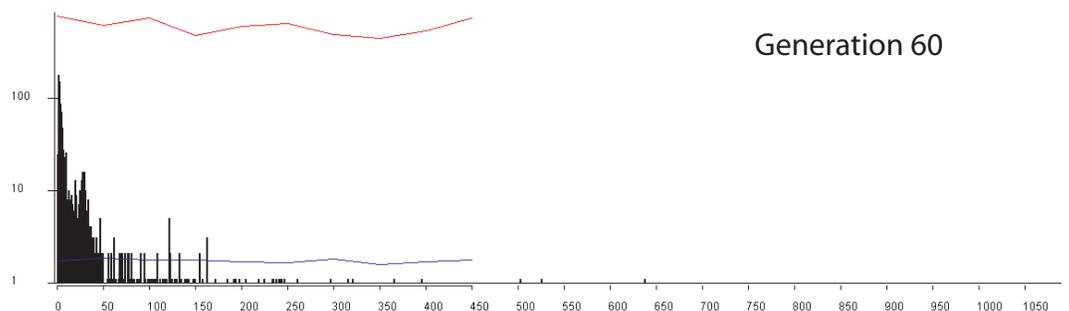


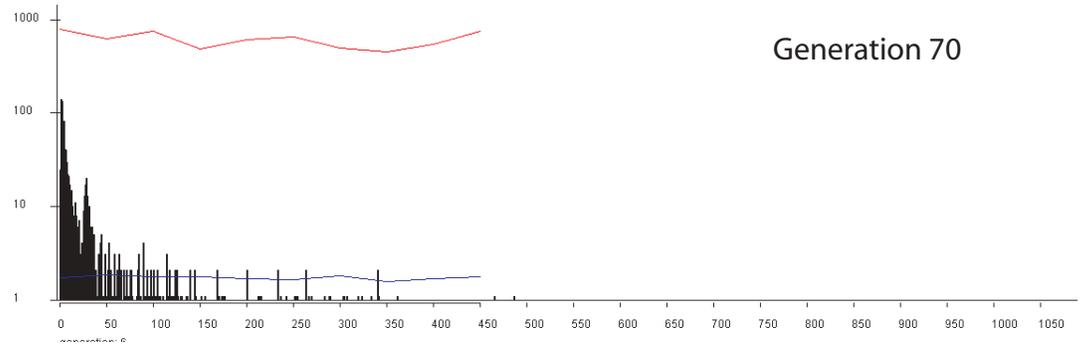


majority of high scoring individuals are the ones creating diagonal patterns which are very economical at covering large surface area through the toroidal wrap around space once they have found a good angle. To score high it is required that their lines of ruling conform well to the surface features. Once a FSA has a successful way of handling the normal adaptation it reaches very high scores by going more or less straight on its diagonal tracks. The more interesting strips are doing less well in general because they need more steps to adapt their

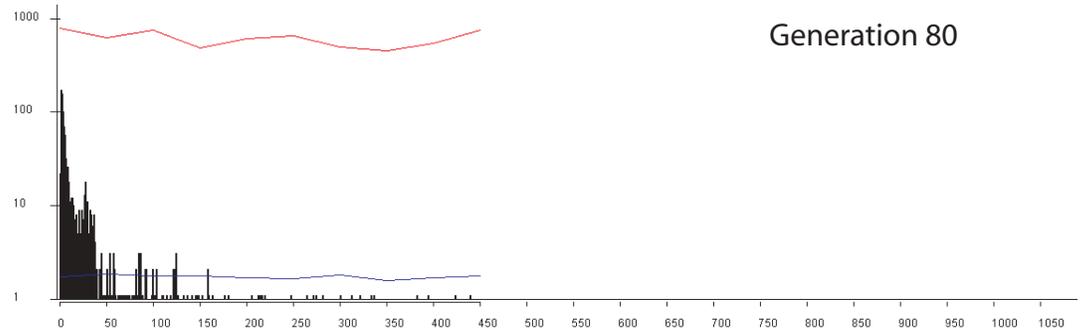


lines of ruling to the normals on the surface which costs extra steps. And although self intersection does not score extra points the overlay in the diagonals is still more effective than the criss cross webbing of the more irregular patterns. It is probably a good approach to limit the successful score window to a middle region rather than to the top scoring individuals in order to diversify the outcome of evolution. Although this has been done on a small scale the results are not dependable indicators of whether this is a feasible approach yet.

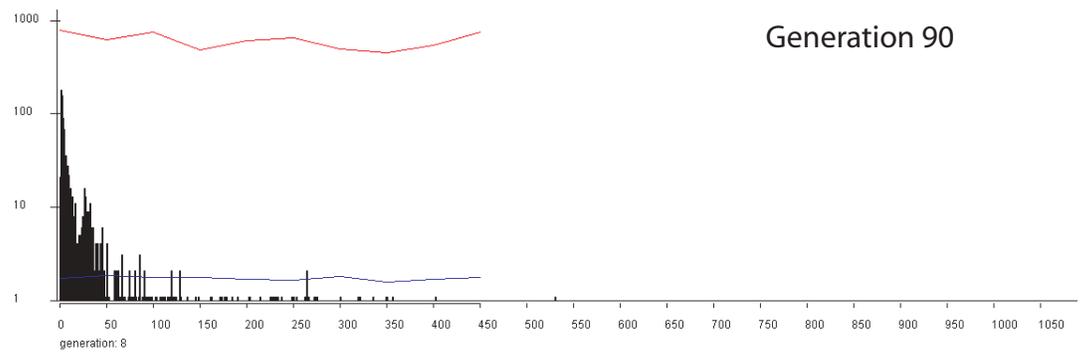




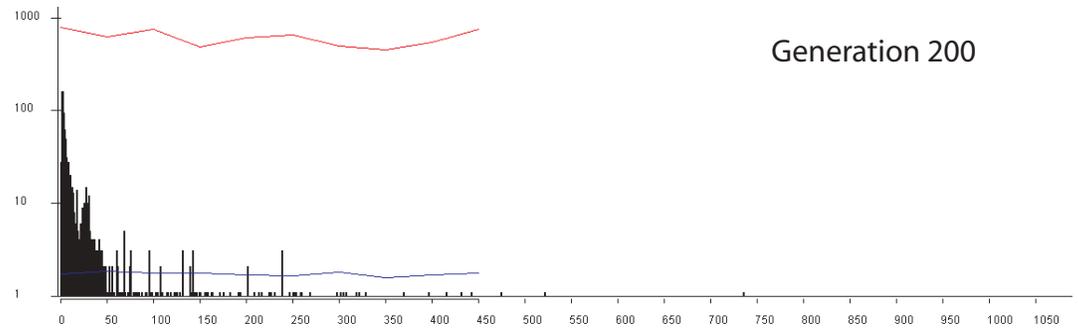
Generation 70



Generation 80



Generation 90



## Strips results

The resulting phenotypes, the strips on the surface present a wide variety of shapes and forms and it is very hard to evaluate them. On level is to look at the scores and therefore see there overall compliance to the normal test. In comparison to the number of steps that gives some measure of how successful the individual was in constructing a phenotype in the surface environment. But there are of course also functional and stylistic consideration that are not necessarily captured by a simple ranking based on the current score implementation.

The following pages show a hierachy based on scores and some very view examples of phenotypes in relation to their scores. A very interesting exercise is also to set the program up to display phenotypes within a certain score region and watch what is produced on the fly while the program tests and runs the strips on the surface. If one finds an individual that one likes one can capture that genome and store it for later closer inspection and for exporting it to rhino to have it be drawn on the original NURBS surface to be able to construct a physical model from it.

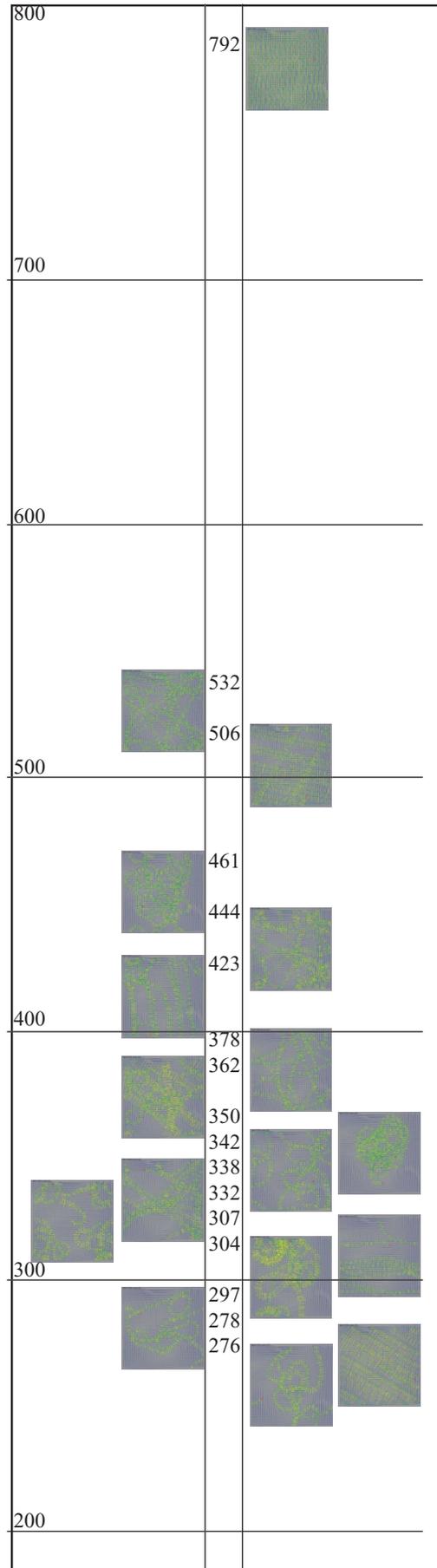
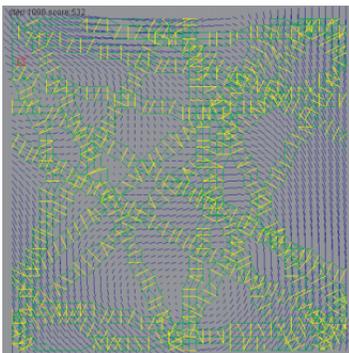
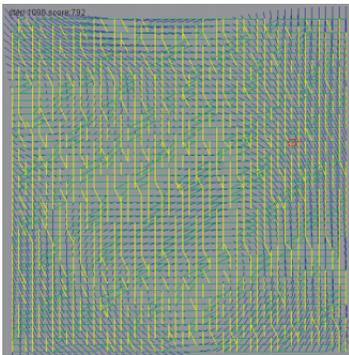
The following pages show an excerpt of the variety of strips in the environment.



## Ranking

To the right one can see a diagram that gives a ranking of the produced strips based on the resulting scores. One can find one of the somewhat parallel/diagonal strip pattern very high up on top of the scale. The upper middle region is dominated by criss-cross type strips were the creature follows to some extent the surface features directly by turning and varying its strip width and thereby weaving a pattern across the surface. In the lower middle region one can find the circling type strips, that "scribble across the surface often self intersecting their own path and often creating knots and big blobs of surface patterns..

By creating such a scale it is possible to fine tune the results by adjusting the score region that is selected for reproduction and mutation to a region that contains the individuals with the desired visual results. Of course it is not guaranteed to produce only strips of that kind since diagonal types that do not perform so well are also selected, but it gives an additional measure of influencing the outcome of the process.

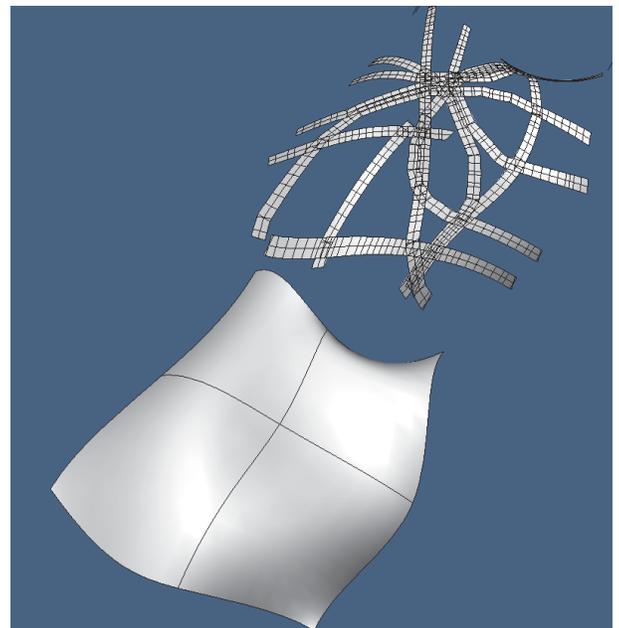
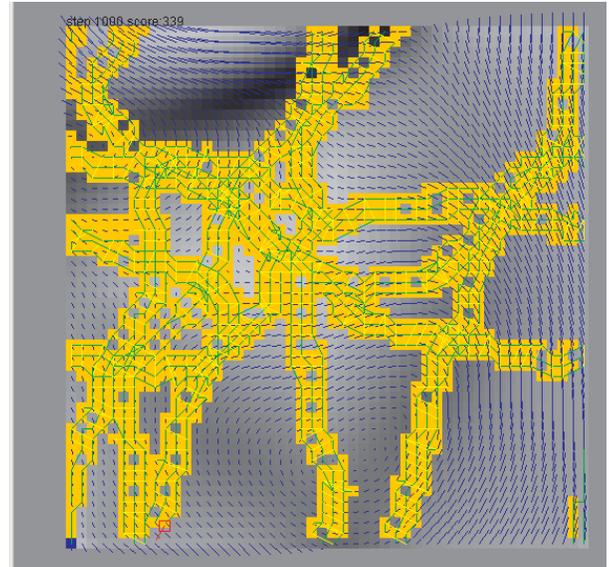


## A "crisscross strip"

The following two pages show the outcome of a strip creature that could be attributed to the crisscross type. It scored very high despite of the relatively small surface area it is covering which indicates a very good performance in fulfilling the normal condition. The image on the right shows the covered surface in yellow against the surface curvature coloring in the untouched regions..

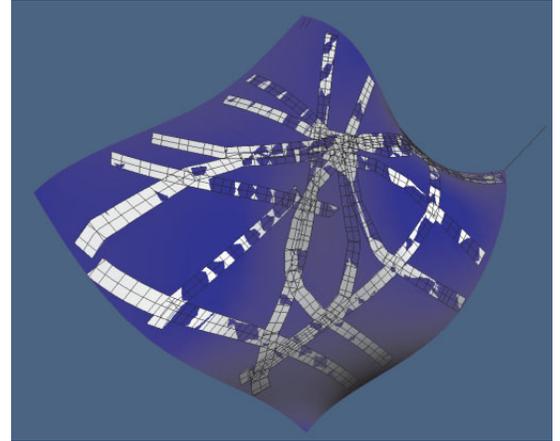
This strip was chosen to show an alternative approach towards producing strips for a surface construction to the more regular isoparam curve based once shown earlier in the paper. It is not very refined and presents one with many problems if one would want to resolve it into a buildable scheme, but the strips form a good bases to work from.

The lower image shows the below the NURBS surface the environment is constructed from and in the upper part the strips mapped from UV space back onto the NURBS surface. The lines of ruling are lofted to create one dimensional curving strips that are developable and could be constructed out of sheet metal for instance.

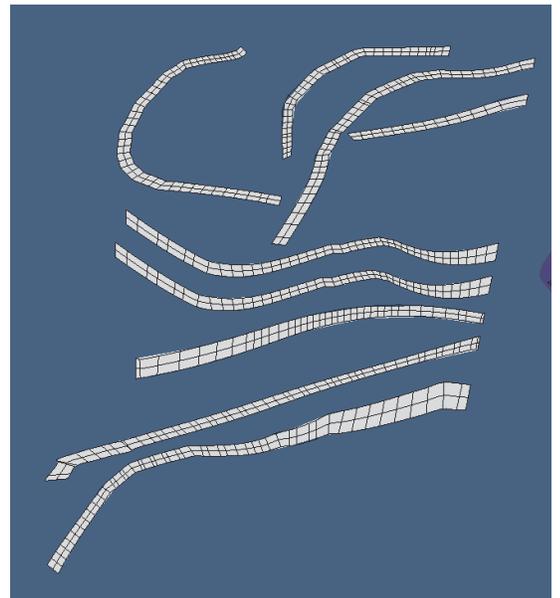


## Visual comparison to original surface

The picture on the right shows both “mother” NURBS surface and resulting strips superimposed. The mother surface is blue and the grey areas are the parts of the strips that are on or slightly above the mother surface.



To prove the developability the resulting strips are being developed onto a flat plane to show that their production out of sheet construction material like sheet metal or wood is possible. The self intersection and overlay and unresolved connections and structure are of course major problems to remain unsolved, but that was not the focus of the current approach.



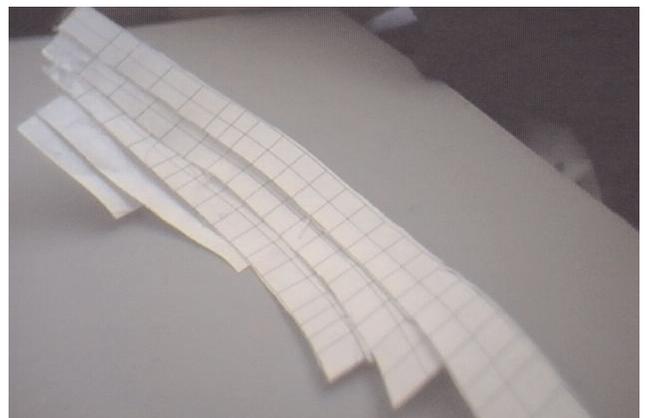
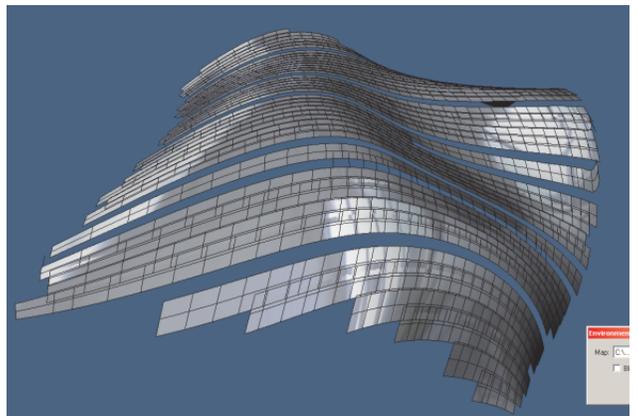
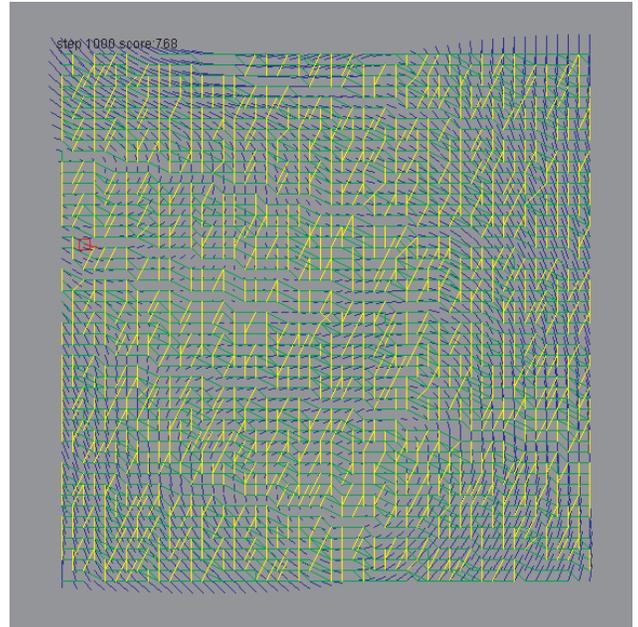
## A "diagonal" strip

The following two pages show one of the highest scoring individuals. It falls into the category of diagonals strips that follow more or less parallel paths in a variety of angle diagonal to the surface uv grid.

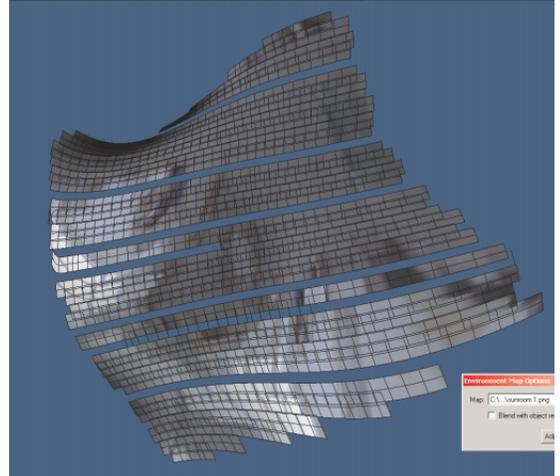
These surfaces score very high due to their ability to cover large areas with relatively few steps and in a direction normal to the direction of the curvature ridges to maximize the step length.

Although the results look very boring in uv space when mapped back onto the three dimensional NURBS surface the distortions and the hugging of the curvature produces very pleasing results. Further automation between the GA algorithms that is currently running in Java and the exchange of the data back into rhino, which currently happens through file transfers would allow a large set of strips in uv space to be explored in 3d space and therefore a better overview what works well.

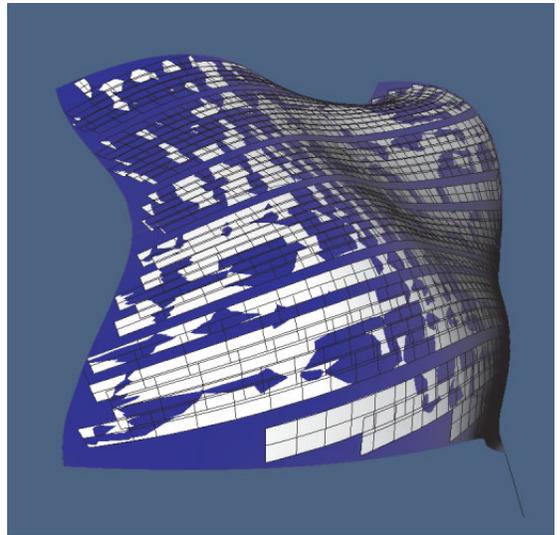
A very small paper sketch of the front corner of the surface using a part of the resulting strip.



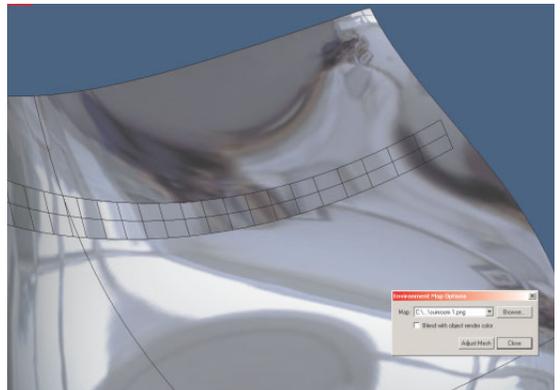
The surface modelled with strips and rendered using an environment map reflection model that allows the evaluation of surface curvature very well. This is a very precise although visual method of evaluating the curvature of a geometry.



Again the overlay of the two surfaces, Blue the mother NURBS surface with two dimensional curvature and grey the strips riding on it with only one dimensional curvature and developability.



Where there is one dimensional curvature features in the mirror image tend to form stripes where there is two dimensional curvature there tend to be blobs.



## **Conclusion**

The combination of different models for modelling embodied intelligence proved satisfactory for me. I chose elements of the Braitenberg vehicles, the artificial chemistry and ants evolving on trails to combine them into a way to evolve creatures that would produce strip geometry with desired properties of developability without constructing them directly but rather let a variety of approaches evolve.

One interest of mine is how to express design intention in such a system, whether it is most successfully done through the fitness function or whether it is better accomplished through the selection from groups of results by a designer during or after the process.

This paper demonstrates the possibility of evolving creatures that produce geometry according to geometric parameters set up by the designer.

In further explorations I would be very interested in exploring this approach further and coming up with models that allow for more complex interaction between different features of the phenotypes and the guiding design envelope.