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# Performative walls: 5-axis subtractive machining on planar surfaces

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## Abstract

Subtractive machining is a digital fabrication process that consists of using digital data to manufacture physical prototypes with machines. The current work investigates subtractive machining of patterns on planar surfaces with an innovative and experimental approach and the goal is to achieve different visual effects for market-oriented applications such as wall paneling, therefore focusing on appealing designs of easy manufacture and reproduction. The method applied was to first generate toolpaths parametrically, then simulate using CAM softwares and finally fabricating prototypes with a 5-axis CNC machine.

**Keywords**: Digital Fabrication, Parametric patterning, Solid Surface, 5-axis Subtractive Machining , Wall Panel,

## Summary

1. Introduction
2. Overview
3. Preceding studies
    3.1. Manual milling
    3.2. 3-axis CNC milling
4. Patterning generation
    4.1. Two images pattern
    4.2. Shadow pattern
    4.3. Curve pattern
5. Prototyping
6. Conclusion
Acknowledgements
References

## 1. Introduction

Digital fabrication can be divided in two main categories: additive and subtractive techniques. The first one is based on the addition of material to form a target geometry while the second one relies on the removal of material from an initial stock in order to achieve a target geometry. This paper focuses on the latter, more specifically in milling panel wall patterns with Computer Numerically Controlled (CNC) machines.

However, there are distinct ways of digitally fabricating patterns in which the kind of machinery and material type have a great role on how to generate the toolpath and how the final prototype turns out. Since most panel walls are thin and flat, the existent examples of digitally fabricated panel wall patterns are limited to up to 3-axis CNC. Therefore, this research investigates patterning with 5-axis CNC machines, that allow more DOF (degrees-of-freedom), which is liberating and challenging at the same time.

Further constraints such as material of choice and the type of 5-axis CNC were defined by a partnership with Sumeplast, a Spain based company specialized in mechanized manufacturing with CNC and laser cutting. The material used is solid surface, a synthetic material commercially known as Corian® by Dupont™ and the machine type is Rierge 5 axis (EasyNest - 4021-5) with milling bed size of 4000mm x 2100mm x 400 mm Z (figure 1) [1].


Figure 1: Rierge 5 axis (EasyNest - 4021-5) Numerical Control Machine [1]

The methodology applied to achieve the objective of creating patterns and toolpaths compatible with 5-axis milling on solid surfaces consisted of three main phases: the study phase with manual milling and 3-axis prototyping experiments on Corian, followed by the design phase of parametrically generating patterns on Grasshopper and Rhino while constantly simulating the milling process with RhinoCAM and lastly the prototyping phase.

## 2. Overview

In the digital architecture world, subtractive manufacturing is widely used to develop many construction elements. The most commonly used fabrication procedures are with 2.5/3 axis, consisting of the X/Y axis (sideways) and the Z axis (up and down) movements to subtract material from a given stock on a platform. The initially CAD originated design is translated to toolpaths (G code) in a CAM software and the generated data is sent to the milling machine so it can process the fabrication procedure. Nevertheless, in the past few years the use of complex geometric shapes and forms in architecture have increased, developing a need for more advanced machining operations. Various 4/5 axis machines with 6 axis robotic arms were developed to fulfill complex geometric fabrication work.

5-axis machining works similarly to a 3-axis but with extra two degrees of freedom. These two additional axis open up a lot more milling possibilities, allowing the fabrication of complex surfaces. There are many different types of 5-axis machines, but mainly they are categorized as Horizontal Machining Centre (HMC) and Vertical Machining Centre (VMC). In HMC, the spindle is located in the horizontal organization with a better efficiency over VMCs for mechanical parts. The machining keeps the milled chips from falling off the working table. In VMC, the spindle position is always vertical and it works on gravitational consideration, removing the material from the stock and allowing the waste to fall down directly without getting deposited on the material [2].

*"Every block of the stone has a statue inside it and it is the task of the sculptor to discover it"*

- Michelangelo (1475-1564)

5-axis machines are capable of milling five different axis at the same time (figure 2), which enables the manufacturing of sophisticated shapes in a single run. They are also known as single setup machines as it does not require a continuous change of material. Once the material is fixed, it can be milled on all its 5 axis and, except by its base plane, all five other planes can be milled easily without having to displace the stock.

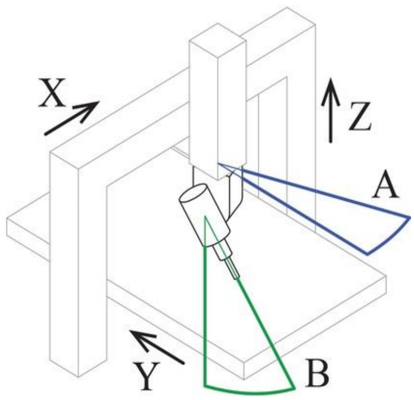


Figure 2: 5-axis machining different axises [3]

## 3. Preceding studies

Before starting to generate patterns, two studies were carried out in order to better understand the possibilities and constraints faced when milling with 5-axis and using solid surface: a manual experiment using stocks with similar densities as the target material and drills with different tool bits; and a 3-axis milling experiment with a 12mm Corian sheet at Medio Design. The manual study was performed in two different phases:

The first phase focused on the subtraction of material with 5 different types of tool bits ranging from 0 to 75 degrees in angle variation and several depth levels (figure 3). It helped to understand the resulting shadow effects derived from holes with distinct diameter, depth and angle.

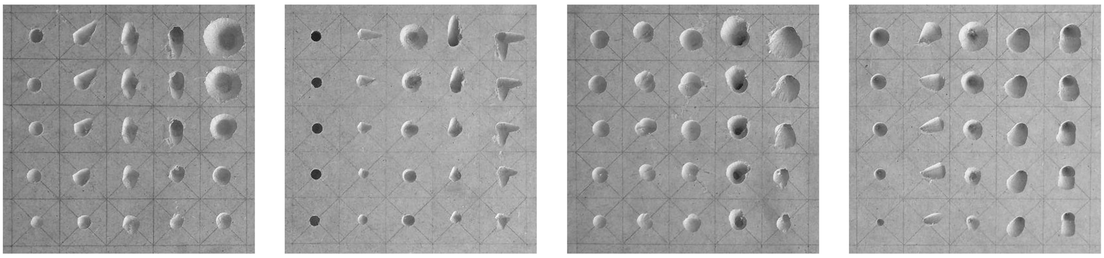

Figure 3: Physical milling test on MDF aiming for different depths and end section

The following phase was to develop patterns using a base grid and one tool at a time with different cutting angles and depths. This test focused on getting as many as possible milling outcomes while using the same tool bit and cutting the material with different depths and it was possible to perceive the distinct footprints each bit was able to create (figure 4).

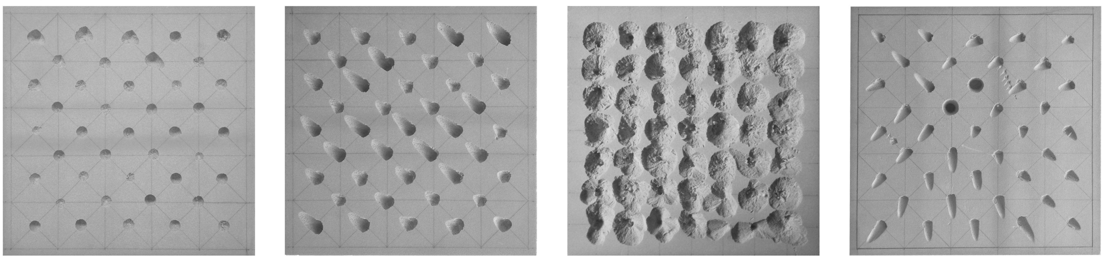

Figure 4: Physical milling test on High Density Foam aiming for different patterns

The second preceding study with the 3-axis CNC at Medio Design allowed a greater perception of the material texture, dimensions and sound when milling. Four different patterns were tested:

**Pattern 1:** In order to verify the material transparency scale and also to understand the milling of a set of curves with greater depth, this pattern was designed using planar curves with cutting depths ranging from 1.5mm to 11.2mm. The tool used for the milling was a ball mill with 38mm diameter. The distance between curves was half the diameter of the tool to achieve a smooth intersection at the end of the curves (figure 5).

Figure 5: Pattern 1

**Pattern 2:** Since milled shapes can generate interesting shadows, this pattern was developed aiming to understand the casted figures from a predefined point light source. The distance between the curves was 20mm and the tool used was a 19mm ball mill, which resulted in small thin walls ranging from 1mm to 3mm between toolpaths according their sinuosity (figure 6).

Figure 6: Pattern 2

**Pattern 3:** Initially with the use of point attractors, waves were generated and movement was added to them with noise so an undulated surface could be formed. Then the surface was sectioned to get a set of curves for milling. The tool used was the 38mm ball mill and the curve depth was ranging from 2mm to 8mm in Z axis. Due to the varied depth, the intersection between two milling paths resulted in very different shapes (figure 7).

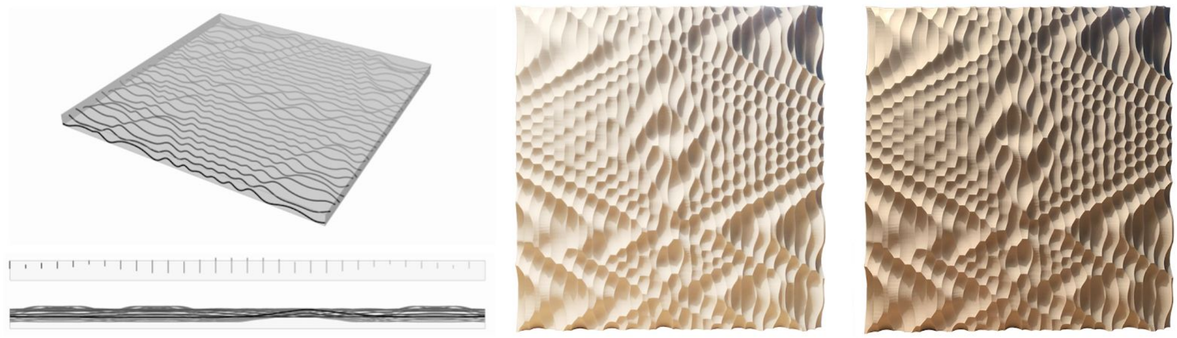

Figure 7: Pattern 3

**Pattern 4:** With the intention of creating curves in X/Y/Z axis, this pattern was generated with non planar curves for a smooth movement of the milling tool. The test was also conceived to perceive the connection between two panels. The cutting curve was along the geometry to provide a better smooth finish. A 38mm ball mill was used to cut the material and the distance between curves was not fixed so it could have different wall thicknesses (figure 8).

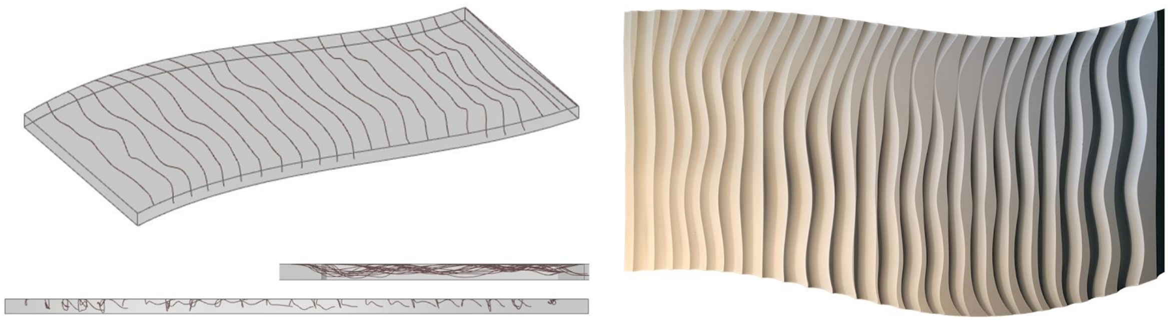

Figure 8: Pattern 4

## Observations:

1. Start point and end point (figure 9): It was possible to observe with pattern 1 that when the start point was at the top of the curve the milling went smooth. But when it got to the end of the curve, at maximum milling depth, the sound was loud and shrill once the the chip load increased because of the sudden material subtraction.

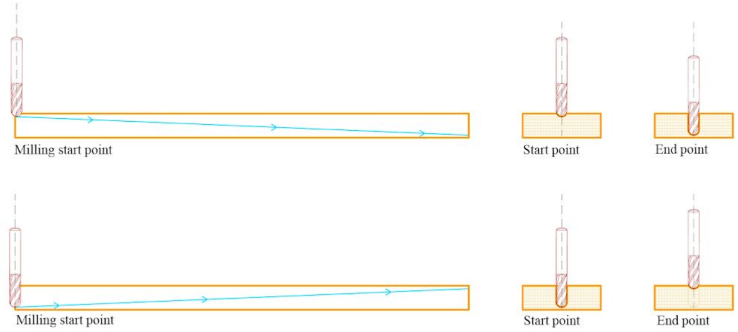


Figure 9: Milling start and end point conditions

2. Curve length (figure 10): In pattern 1, the initial curve is very deep and since the toolpath has the exact curve length needed the edges become vulnerable and tend to break when starting or ending the milling process. The curve depth was ranging from 1.5mm to 11.2mm and the material at the end of the curve lowest point became fragile resulting in the breaking of a small chip. To avoid this situation the curve was extended 10mm outside the stock and the tool engaging speed was decreased.

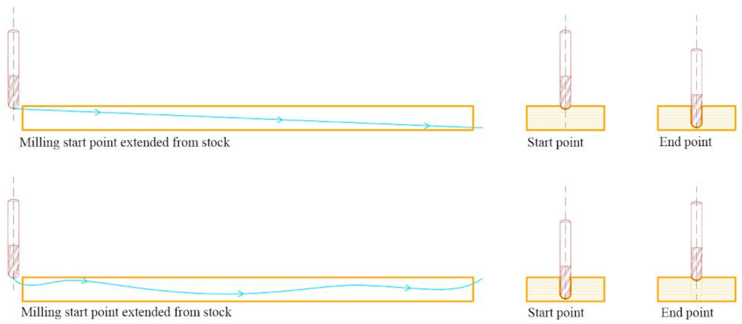


Figure 10: Extension of the curves

3. Material thickness variation (figure 11): Corian sheets are produced by casting, resulting in non uniform thickness across its section. The material used for the initial test was 12mm. In pattern 1 the curve depth was from 1.5 to 11.2 mm which created very thin section at the end of the curves. The cutting depth shouldn't cross the 11 mm depth to avoid material cracking.

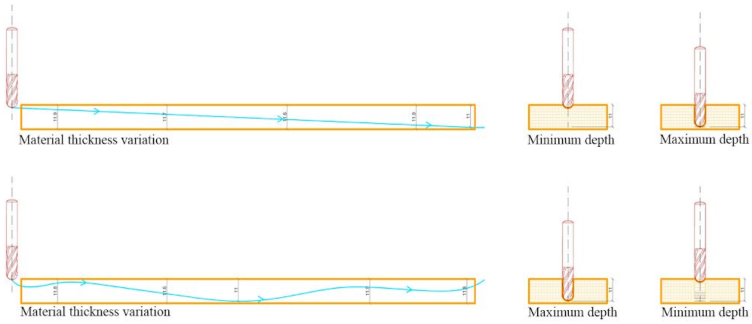


Figure 11: Material thickness variation

4. Material transparency (figure 12): It is possible to achieve several grades of transparency with Corian. Pattern 1 was also a gradient study of such translucency that led to the conclusion that from 6mm on the material becomes semi transparent allowing light to pass through.

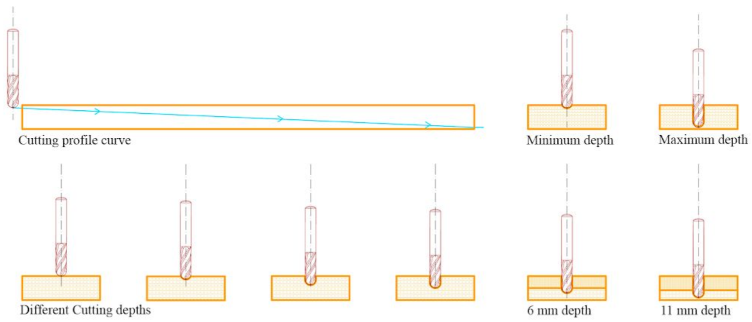


Figure 12: Material transparency

5. Curve direction (figure 13): The direction of the curves is equally important for the machining process. In pattern 3, with given 28 curves the initial milling time taken was 190 seconds because all the curves were oriented in the same direction, and due to this, the tool needed to move to the starting point of each curve after finishing one curve. The solution to this was to flip the direction of the alternate curves, making the end point of one curve next to the starting point of the next curve. The cutting time was reduced to 100 seconds, i.e half of the earlier.

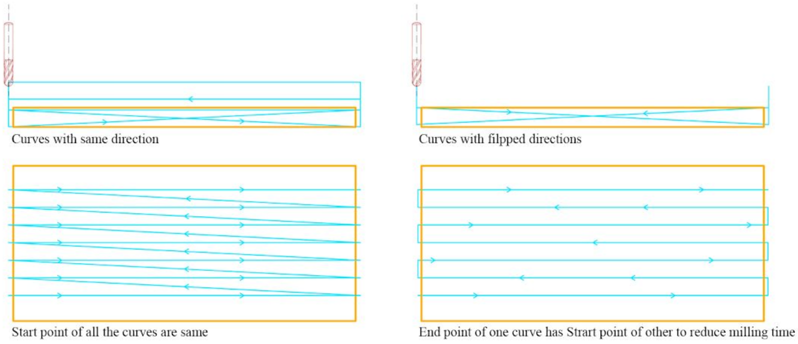


Figure 13: Curve direction

6. Curves distance (figure 14): The distance between the curves is equally important as the depth of the curves. In pattern 1, 2 and 3 the distance between the curves is according to the tool used, this decides the wall created between two adjoining curves. In pattern 1 there are sharp edges created because the distance is exactly the same as the tool diameter. On the other hand, pattern 2, 3 and 4 resulted in very different edges because of the nature of the curves and also the distance between the curves was greater than the tool diameter.

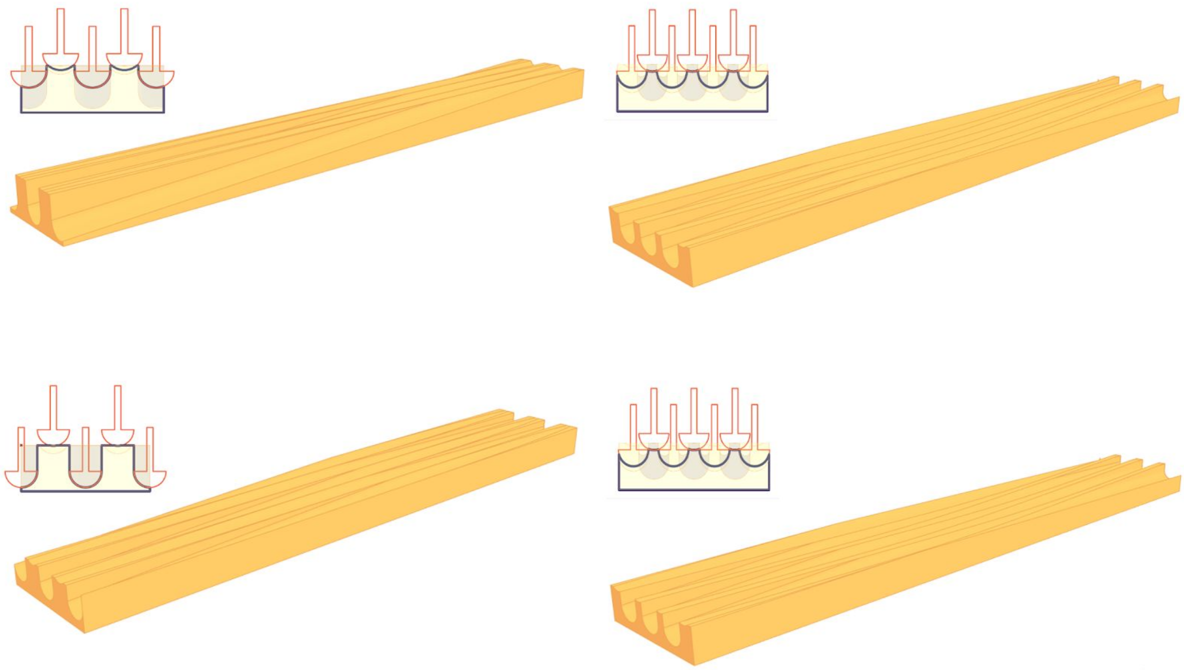

Figure 14: Distance between curves

7. Tolerance and precision (figure 15): In pattern 4, the edges are not straight. To match the adjacent panel pieces, the milling has to be done on the offset of the exact same curve at ½ mm considering the tolerance and precision of machine to be used. The edges to be cut should be carefully developed to show continuity when joining two panels together.

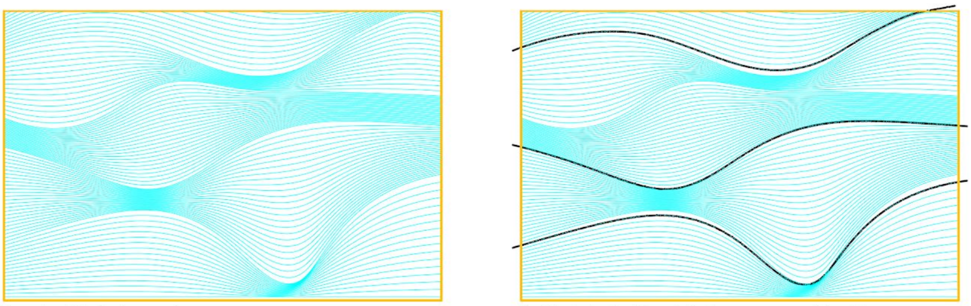


Figure 15: Tolerance and precision

## 4. Patterning generation

A pattern is the repeated reproduction of elements until they form a design or composition. The main goal was to create patterns with optical illusions that interact with the viewer's perception.

The first patterning attempts (figure 16) were developed by reproducing images provided by image sampler with different sized holes. However, these initial strategies were left behind due to the increase in tool traveling time during the milling process.

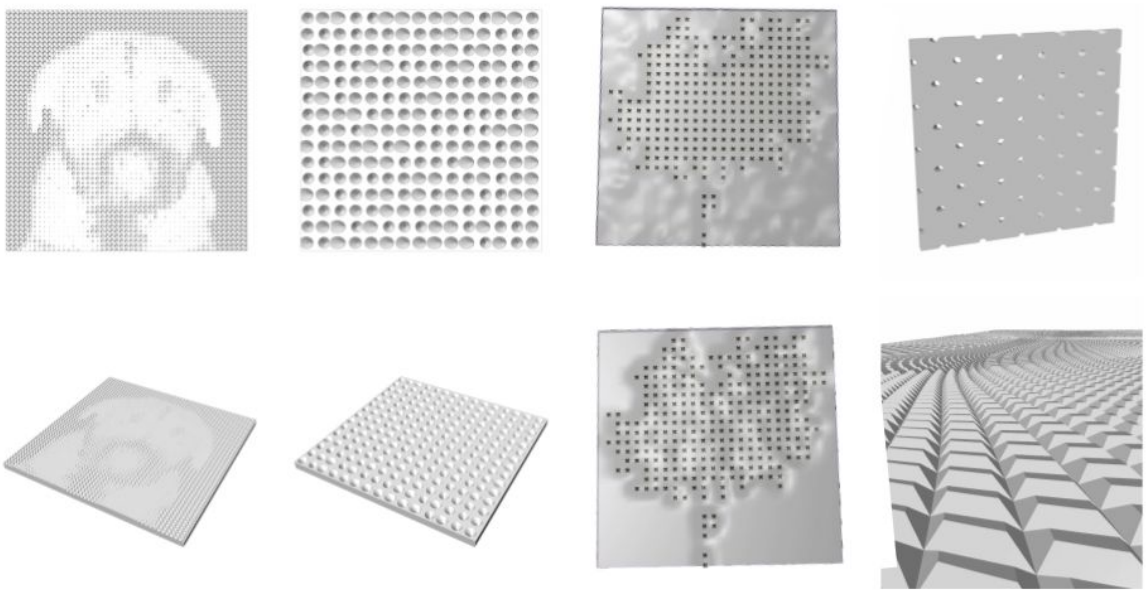

Figure 16: Initial patterning attempts

### 4.1. Two images pattern

This pattern was developed with the intention of surprising the viewer by revealing an image as the observer passes by. It is already well disseminated in the wall paneling market the possibility of customizing a milled surface with a specific image such as logos and portraits. However, what is not yet explored is the possibility of creating an optical illusion of milling two images at once, but only seeing one at a time according to the angle of observation.

The algorithm behind this pattern (figure 17) is generated with the input of two images. Initially, the target surface is subdivided in a grid of points, that are later separated in intercalated rows, each one designated to one of the desired images. The points are moved accordingly to the values retrieved from the image sampler and are then interpolated, forming two sets of curves. From these two groups of curves, it is generated a tween curve.

These three sets of curves are the ones used as toolpaths: the first two groups are milled as 5-axis operations, each one with opposite angles according to the desired perspective. In the simulation it was used 45 degrees. And lastly, the tween curve is milled as a valley in 3-axis between the previous ones

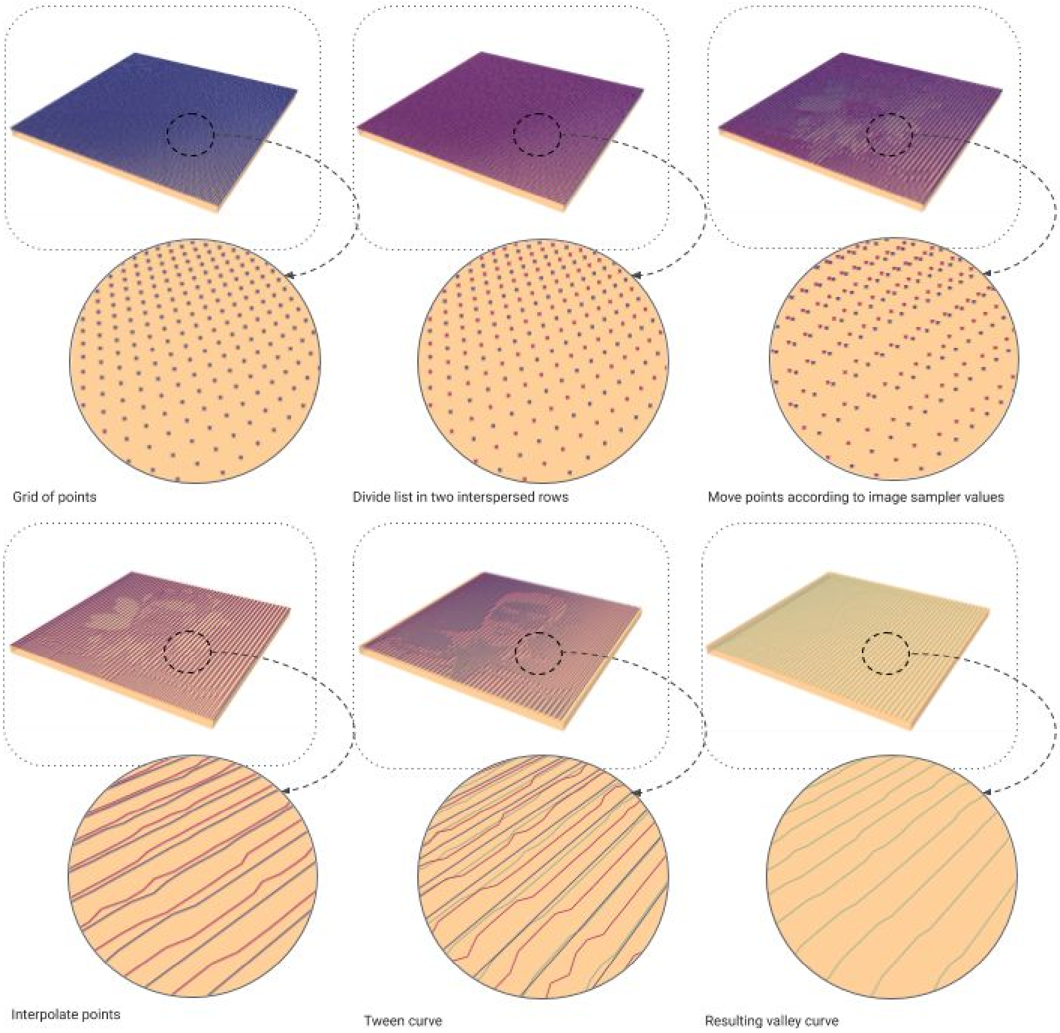


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Figure 17: Pattern generation process

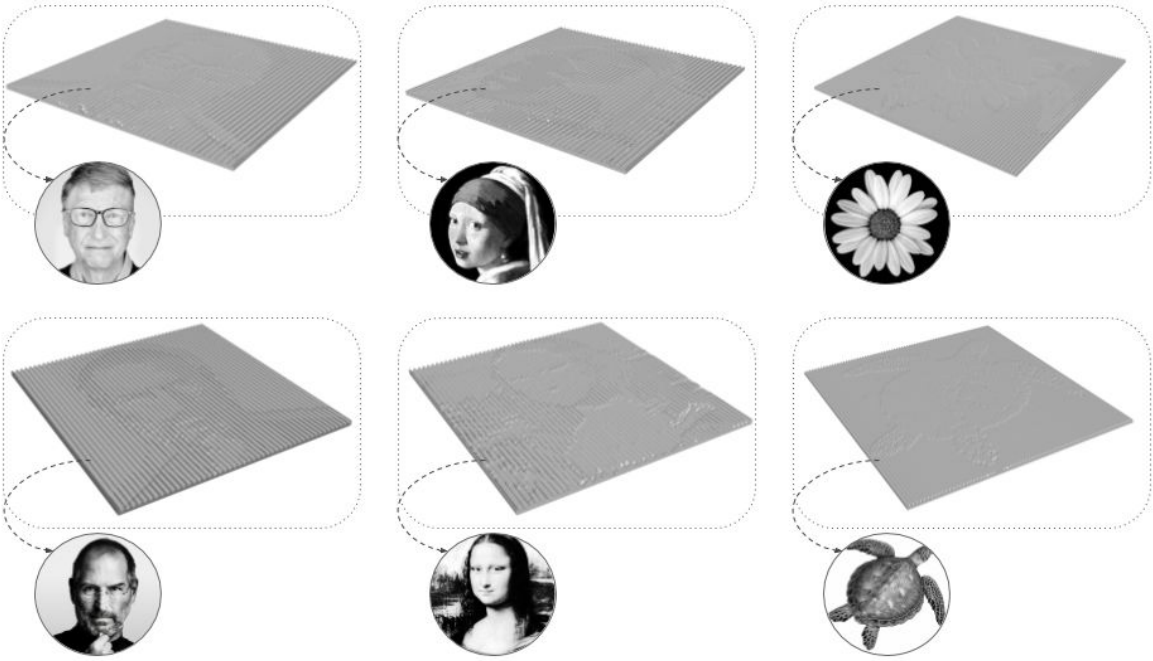

Figure 18: Pattern options

**4.2. Shadow pattern**

The objective of this pattern was to interact with light as a way of creating figurative shadows. By changing the light source location, distance and angle, the resulting images also change. It was applied the anamorphosis technique of geometrically projecting distorted images on a surface that can only be recognized from a specific point [4]. In order to achieve such effect two different strategies were approached: first placing the light source perpendicularly to the panel normal to form a profile shadow and then placing it behind the plate.

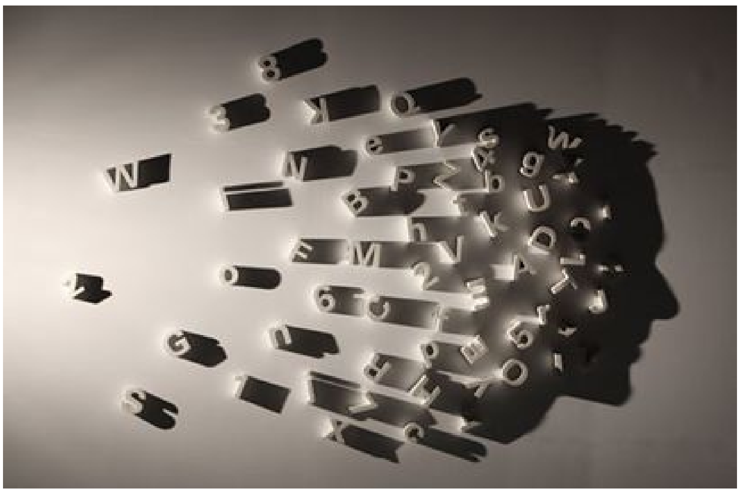

Figure 19: Korean artist Kumi Yamashita's installation "*Profile"* at Microsoft Art Collection, Washington, USA 1994

**Method 1: Profile projection**

For the development of this method, the point of light is located outside the panel, perpendicularly to the surface normal. Once its location has been defined, a curve with a figurative profile is placed on top the surface between the source of light and a second surface where the image will be projected, however closer to the edge where the light is, otherwise the shadow will not be well seen. The curve is divided into multiple points from which visual rays will be traced to the defined point of light. By extending these rays, they will intersect with the projecting surface. After obtaining the points of intersection and interpolating them, it results in the final shadow.

For the main surface of the panel it is proposed a texture completely independent from the shadow, since the light rays will not interact with the rest of the pattern. Using the upper surface of the panel as a base, a series of lines are created that will then be divided into two groups, the odd and even, and later divided into points, divided again into even and odd. One group of points is moved up and another group is moved down, then they are joined and interpolated into curved lines. While in the even group the curve rises, in the odd group the curve descends, forming an interesting set of highs and lows on the surface.

It is important to emphasize the main constraint of this technique is the material width. Thicker stocks allow bigger and more elaborate shadows. Since the Corian stock had a restricted width of 12mm, there was not much space to explore the shadow illusion.

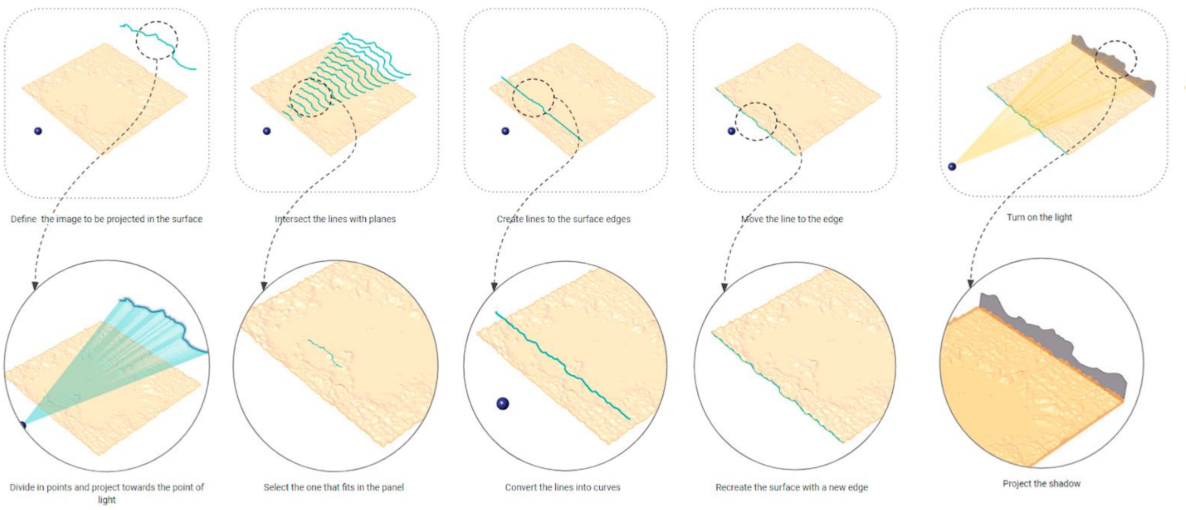


Figure 20: Profile projection shadow pattern process

**Method 2: Posterior projection**

In the development of the second method, the point of light is behind the panel, and it was sought to generate the illusions in two different ways: the first one with the light passing through the material to project a reflection on an opposite surface, and the second one by playing with the material opacity when illuminated.

For the first form of intervention, once defined the point of light, the dimensions of the image and the surface where it will be developed, the image must be decomposed in points and projected towards the panel that will hold the illusion. This projection will result in a smaller and inverted version of the image. The distance between the panel to the projection surface is determined by the size of the final hole through which the light can pass, or vice versa, the greater the distance, the smaller the hole will be, therefore it must be taken into account at the time of the manufacturing process.

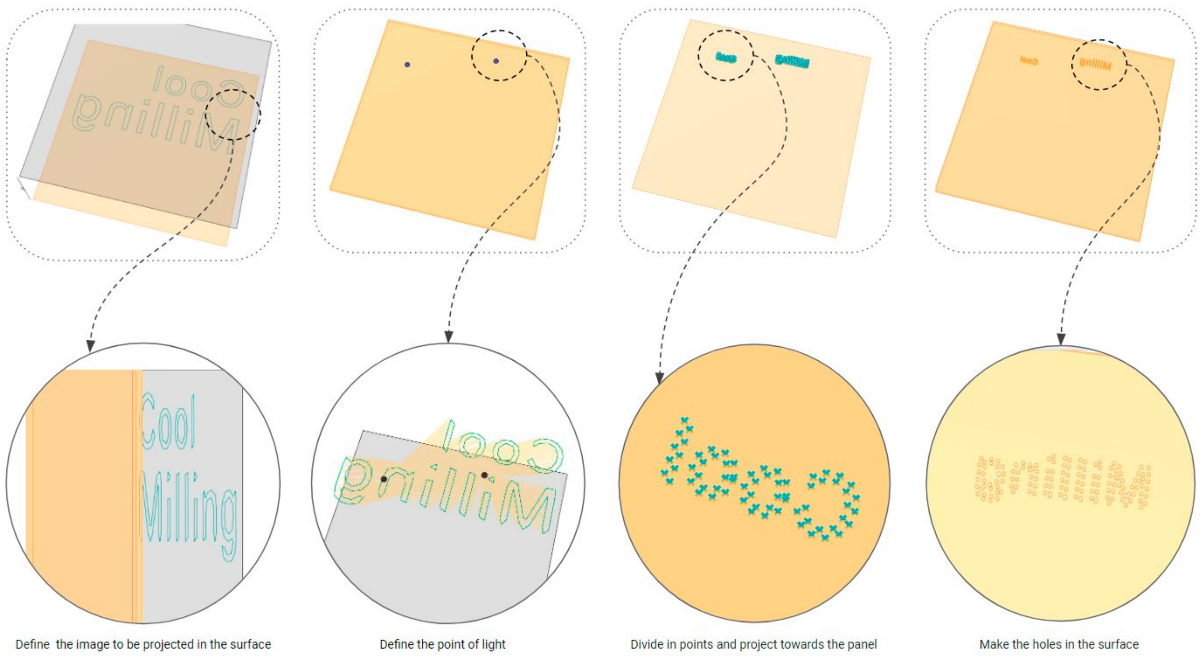


Figure 21: Posterior projection shadow pattern process

And for the second form of intervention it is necessary to take into account the maximal milling depth so the light can be appreciated and it is important that the driller does not exceed this distance enabling light to go through. The chosen image can be directly placed on the panel, decomposed into points, and these points are the ones that should have greater depth when milling so a light refraction can be seen.

Once the points are in place, a voronoi pattern is generated. The largest areas are identified, then filled with random points so a second voronoi pattern with more similar cell areas can be developed. Once the pattern is obtained, all point depths are modified varying in height. For the first intervention points, the height must be equal to the material width so it can be crossed by the tool bit.

In the second case, the image points depth must be less than a third of the width of the material so the light refraction can be seen and for the other points the height can oscillate between half the width of the material and the surface top to distract the observer. When the point heights have been established, pyramidal surfaces are generated, thus forming an interesting set of highs and lows on the panel.

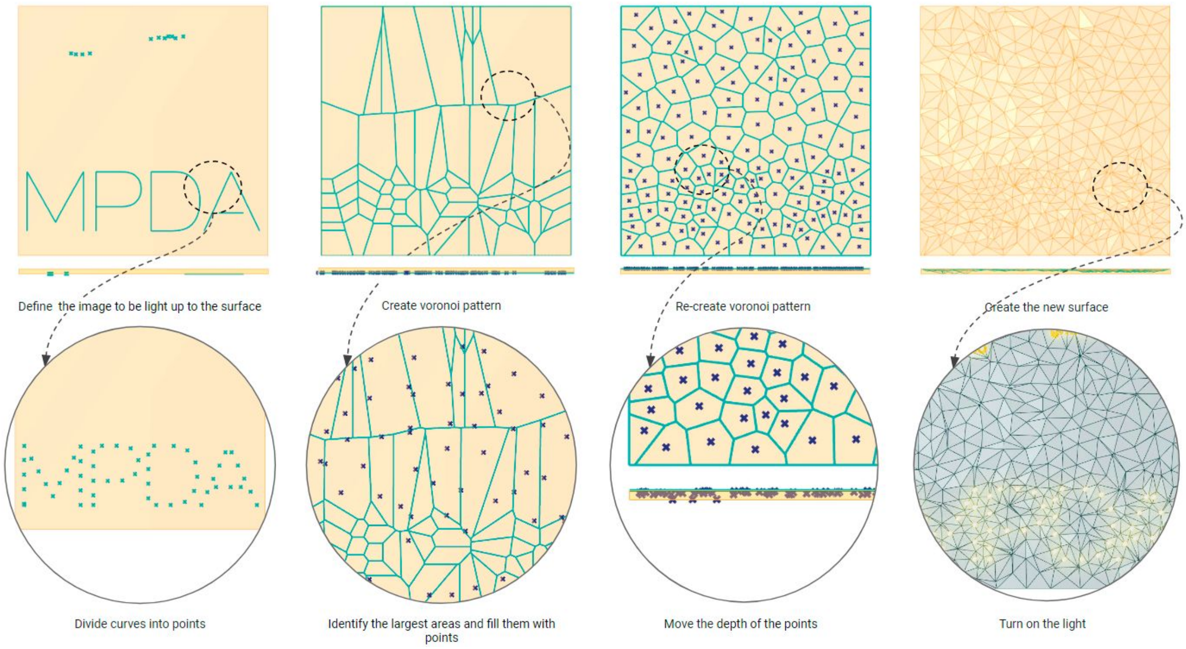


Figure 22: Process to achieve the desired light effect

### 4.3. Curve pattern

The development of this pattern was to comprehend the connection between two or more panels when forming a pattern. This idea of developing joints on a milled surface can be used with the possible types of patterns. The connection between two panels is defined by the same curves from the designed geometry. The profiling curve is always in the same direction of the pattern designed.

The pattern was developed with the set of 2D grid of points on the stock or desired size of pattern. Depending on the direction the network of parallel curves were made horizontally, with the help of the point grid. With the help of few point the curves were pushed away from those points to get the spherical effect (also known as point attractor). According to the side required three curves were overdrawn on the pattern to define its cutting edge. Another two vertical curves were drawn to define the side edges of the panel and other two curves for internal pieces connection. The distance between curves were maintained within 4mm to 25mm to achieve different wall thickness across the length of the curve.

The 5-axis machining of these curves required an angle for the tool orientation. Point on the curves were defined to achieve the angles required for milling. The tool angle was different at each segment of the curve to achieve smooth section. The first layer of milling was the primary horizontal curves according to the angle defined by the point. The second part of the milling was to cut the edges outside of the curves defined. The first sides to be cut were the horizontal curves from the primary curves using flat mill at a 90 degree angle. The milling of the curves were done outside the curve i.e cutting in the valley of the pattern, to ease fixing of the joints. Later, other vertical curves were milled to achieve the linear connection on the edges across the curves milled.

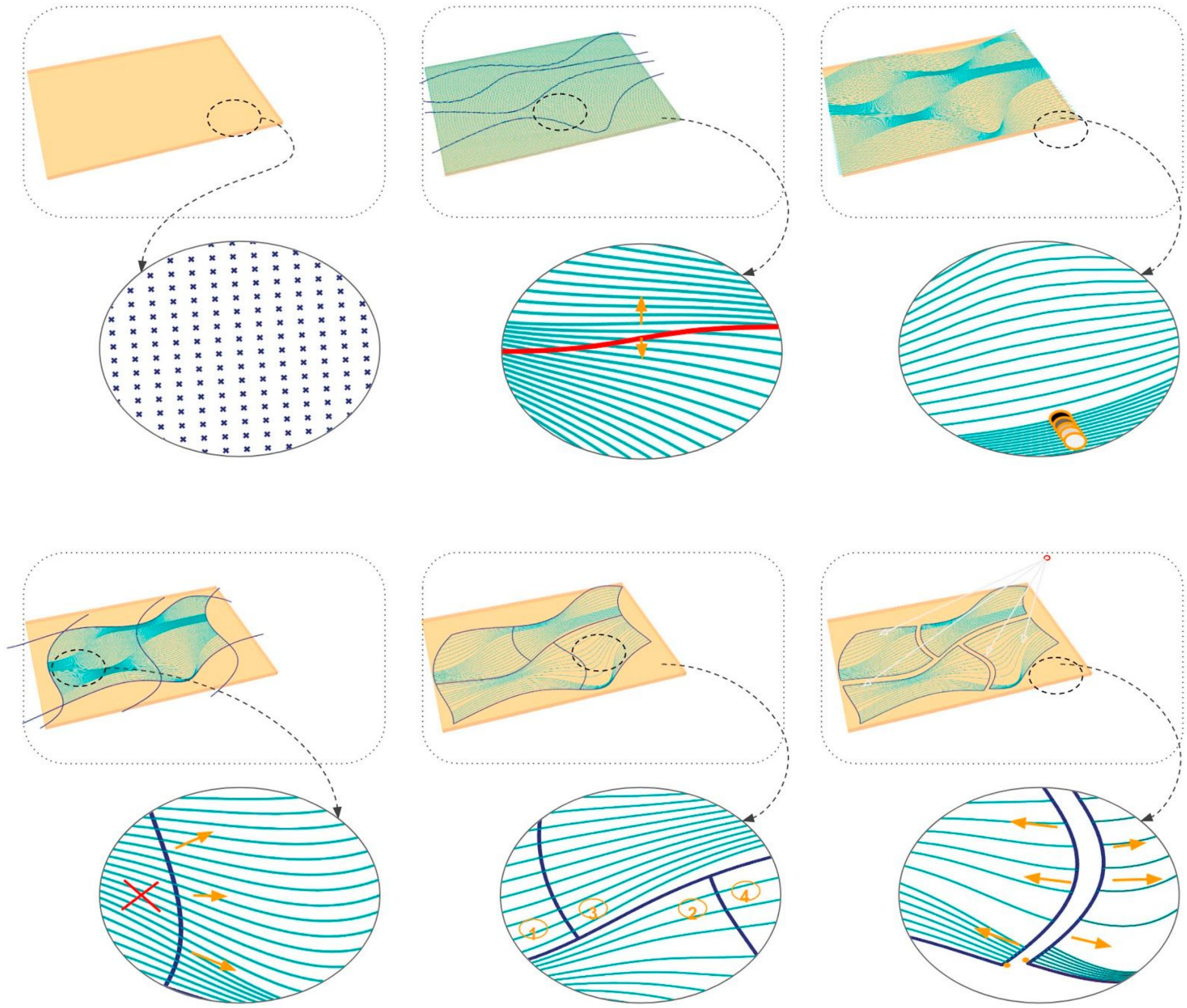

Figure 23: Curve pattern process

## 5. Prototyping

The prototyping process was carried out at Sumeplast, located on the outskirts of Barcelona, where the different designs explained above were tested. The biggest challenge at this stage was to translate the results obtained through RhinoCAM to the program with which the company works, TopSolid, however positive results were achieved.

**Two images pattern observations:**

1. Images with high contrast work better than grayscale
2. Parameters than influence on the outcome:
    - Tool bit angle
    - Toolpath depth
    - Distance between curves

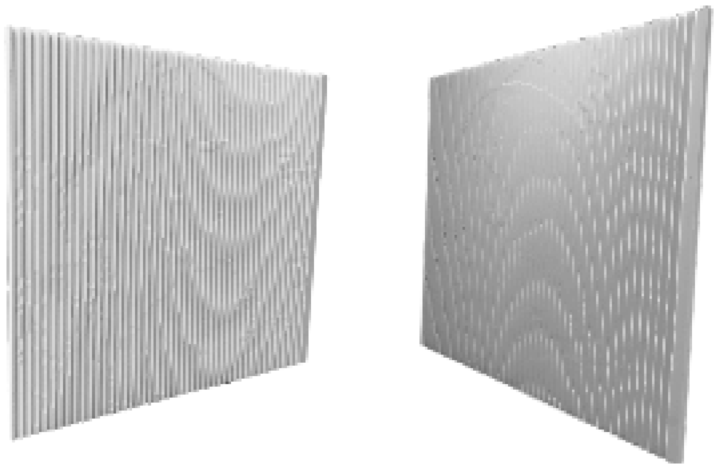

Figure 24: Pattern generated to play with perspective

**Shadow pattern observations:**

1. The milling simulation was through the surfaces normals in which the tool made the movements practically automatically in the 5-axis as the best way for it to achieve the surface.
2. Unfortunately, the complexity of the surface did not allow the design hypothesis to be tested on the CNC.

Figure 25: Pattern generated to see shadows

**Curve pattern observations:**

1. The distance between the curves defined the thickness of the wall between 2 tool path on the curves.
2. As the tool angle reduces, the surface becomes smoother.
3. Joints of the panel can be designed within the curves, i.e on the path of the lst curve.
4. The profiling tool path should be 1mm offset from the original curve and cutting should be done outside the curve.
5. The tooling angle should be gradually increased or decreased along the curve.

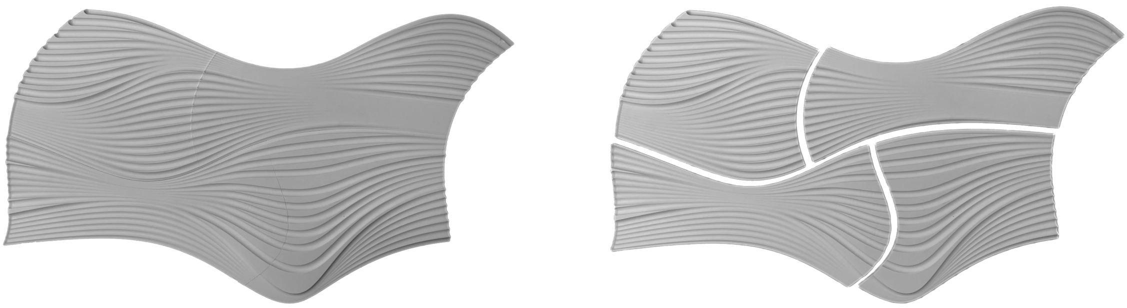

Figure 26: Pattern generated through curves

5-axis subtractive milling on planar material brings up a new series of complex milling strategies into account. The image below (figure 27) explains the 2 degree of freedom that a 5-axis machine has over 3-axis. The tool orientation can be set at any specific angle for a given curve during the milling process. There are various methods to provide normal for given curve or surface depending on the machining process. In this research input parameter for the toolpath are the curves and the direction is defined with respect to the direction on curve and an orientation point of viewer (image 28).

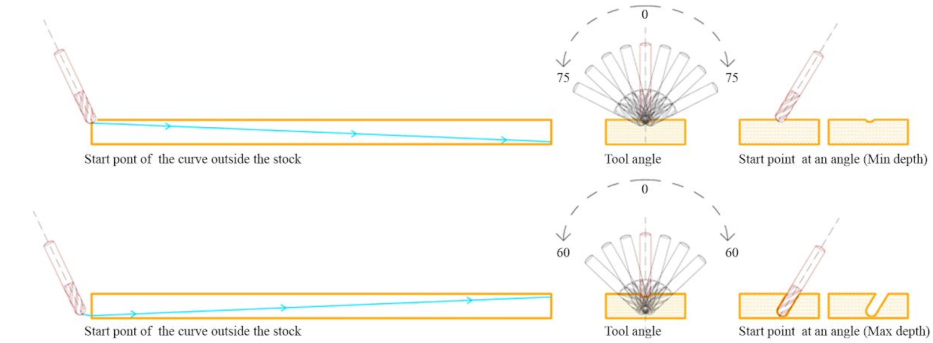


Figure 27: Tool tip orientation to the milling material

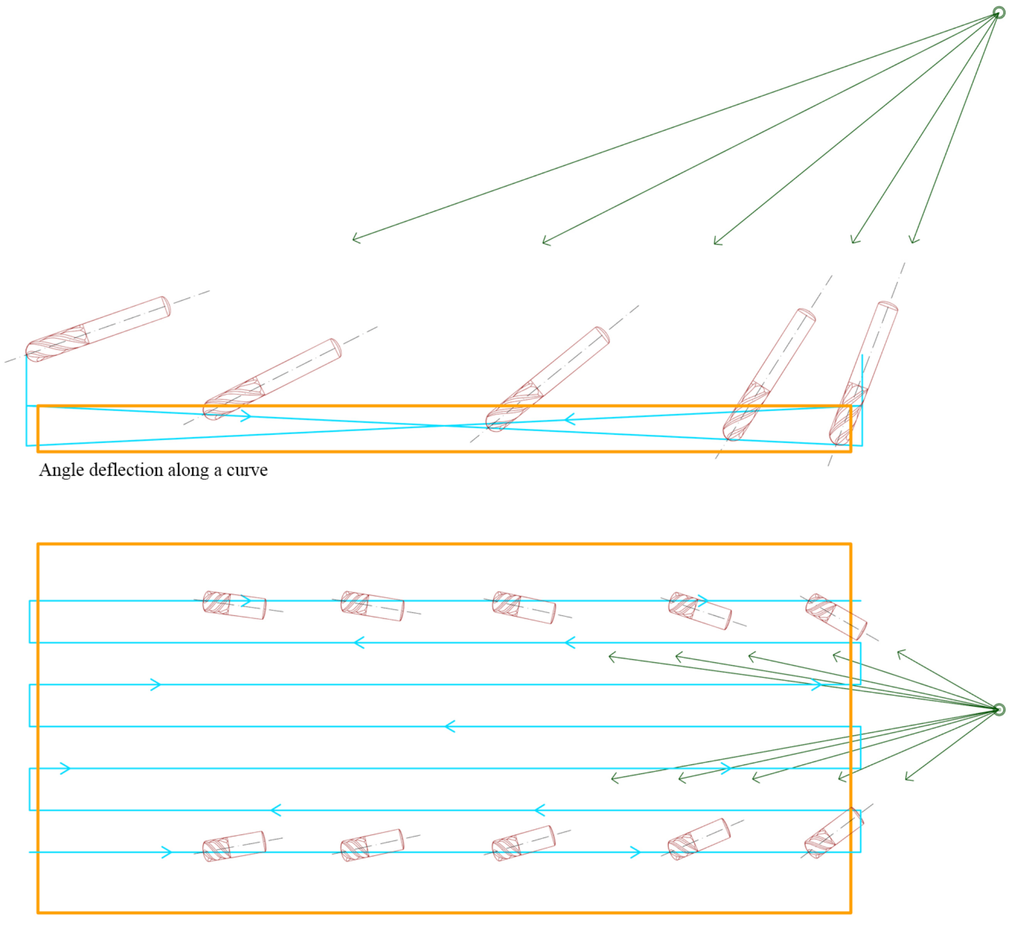


Figure 28: Milling bit Angle deflection

## 6. Conclusion

It is possible to conclude from this research that 5-axis subtractive machining on a planar surfaces allows several different pattern effects that are limited in machines with lower axises number. However these operations with more degrees of freedom are not yet fully explored in this research, but display a great potential for fabrication of complex shapes, not only for wall paneling products but for architecture in general.

This work will continue exploring patterning examples aiming for more innovative and unique wall paneling developed with 5-axis CNC machine.

## Acknowledgements

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