Space Filling Curves for Optimising Single Point Incremental Sheet Forming using Supervised Learning Algorithms

Kunaljit Chadha[1] , Alexandre Dubor[2], Laura Puigpinos[3],
Irene Rafols[4]
[1,2]Institute for Advanced Architecture of Catalonia [3,4]Eurecat
[1,2]{kunaljitsinghchadha|alex}@iaac.net
[3,4]{laura.puigpinos|irene.rafols}@eurecat.org

Increasing use of computational design tools have led to an increase in the demand for mass customised fabrication, rendering decades old industrial CAD-CAM protocols limiting for such fabrication processes. This bespoke demand of components has led to a unified workflow between design strategies and production techniques. Recent advances in computation have allowed us to predict and register the tolerances of fabrication before and while being fabricated. Procedural algorithms are a set of novel problem-solving methods and have been attracting considerable attention for their good performance.They follow a procedural way of iteration with an established way of behavior.In the particular case of Incremental Sheet forming (ISF), these algorithms can realize several functions such as edge detection and segmentation required for optimizing machining time and accuracy.In this context, this paper presents a methodology to optimize long-drawn-out ISF operation by using geometrical intervention informed by supervised machine learning algorithms.

Keywords: *Procedural Algorithms, Incremental Sheet Forming, Robotic Cold forming, Mass Customization*

INTRODUCTION

Current focus on the development of CAD CAM processes is focused on the mass customizable aspect of manufacturing over mass production using the same machine setup. The process of incrementally forming sheet of metal is called 'Dieless Forming' which was patented by Leszak [1] in 1967, much before it could have been machined. The process relates to a method for forming a sheet of material into various shapes of revolution without the use of dies, forms, or mandrels. Ever since, there have been investigations on different ways of plastically deforming sheet metal at a local point to maximize freedom for production [3].

Recently due to the diversity of manufacturing techniques and their productivity, the volume of batch production has gone low resulting in shorter production cycles. Hence giving a boost to more adaptable manufacturing systems.

Figure 1
Picture credits : Hélène Binet, Roland Halbe, Werner Huthmacher. Architect : Zaha Hadid Architects - Innsbruck Railway Station 2007.

Processes such as sheet metal forming have given greater degrees of freedom to architecture and designers. Some architectural projects such as the Innsbruck's Railway station by Zaha Hadid Architects (ZHA; figure 1) have demonstrated the versatility of moulding process combined with CAD CAM techniques. Here each unique panel was manufactured using a moulding process where mould making consumes a tediously huge amount of machining time and material while roughly 98% of the planning, calculation, optimization, tendering and marketing in construction is based on digital data. Along with this comes more and more direct interface between the computerized design process and the physical implementation (Hauschild & Karzel, 2011) [3]. While more and more architects make use of computational logics to embed data into structures, there is also a growing interest in algorithms inspired by Nature that have demonstrated some economic advantage while revealing novel patterns and function.

This paper explores the use of such nature inspired algorithms in the specific case of incremental sheet forming process and discusses its possible economic and aesthetic interest towards machining and performance.

EXPERIMENTAL PROCEDURE

To evaluate the potential of nature inspired algorithms for the production of thin sheet elements, the following experimental setup has integrated a "Space Filling Curve" procedural algorithm with an "Incremental Sheet Forming" robotic fabrication process, later optimised with a "K-Nearest Neighbour" machine learning.

INCREMENTAL SHEET FORMING

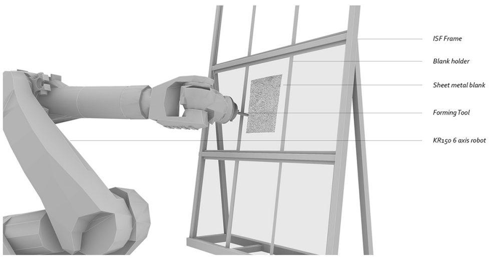
Incremental Sheet forming (ISF; figure 2) is a process which imparts 3D forms onto 2D sheets directly formed by accumulative plastic deformations. It is a stretching cold forming process where the structural capability of the sheet of material is augmented by local surface structuring. This opens up new potentials to structural shapes/forms which could be manufactured out of thin sheets of material.

Customarily ISF systems can be set up with a 3 axis manipulation. For this particular paper, the ISF system was set up on a 6 axis industrial robot with a heavy payload of 120 kgs to allow greater possibilities of manipulation for complex forming (figure 3). The large setup allows more panels to be mounted apart from the system flexibility for individual fabri-

Figure 2
Conventional steps for Incremental Sheet Forming

cation of sheet metal. The purpose of this paper is bifold. First is to optimize the toolpath to reduce machining time of any given geometry as compared to the conventional way. Second is to use this generative toolpath as means of micro-texturing to allow localized surface structuring to introduce stiffness at stressed regions of the desired surface.

Figure 3
Digital robot setup for ISF



SPACE FILLING CURVES

Space filling curves (SFC) is a way of mapping multidimensional space into one dimensional space. It acts like a lace that passes through each cell in the volume so that every cell is visited exactly once. Thus SFC imposes an order of points in a volume. There are numerous kinds of space-filling curves (e.g.: Hilbert, Peano, and Gray). The difference between such curves is in their way of mapping to the one-dimensional space, i.e., the order that a certain space-filling curve traverses the multi-dimensional space. The quality of a space-filling curve is measured by its ability to preserve the locality in progression [4]. Some of the standard space filling exam systems include :

Peano Curve (figure 4): The Peano's curve starts with an initial 'curve', then each element of the curve is replaced by a newly generated path. Shown in fig 04 are four iterations of the Peano's Curve and it's easy to imagine how you can keep doing this over and over again. One would think that if you kept doing this indefinitely, this one-dimensional curve would eventually fill all of two-dimensional space and become a surface [13].

Hilbert's Curve (figure 5): Hilbert's system of curve generation was introduced by David Hilbert in 1892. It describes a logic where the curve visits every point in a square grid with a size of 2×2, 4×4, 8×8, 16×16, or any other power of 2 [5].

Figure 4
Peano's curve logic

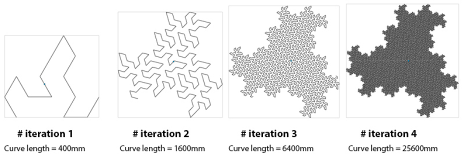
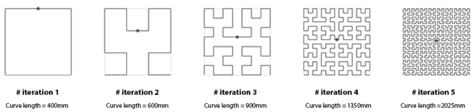


Figure 5
Hilbert's curve logic



Gray code (figure 6): The gray code belongs to a class of codes called minimum change code[6].This algorithm creates the shortest non intersecting curve length in a given space.

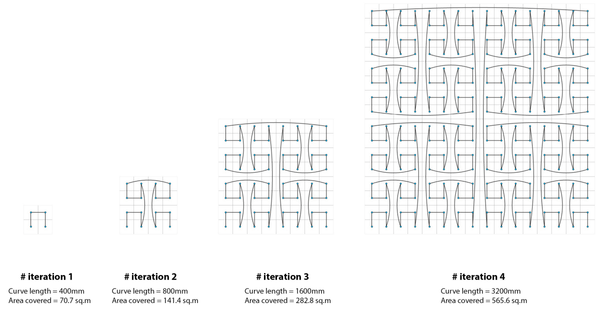


Figure 6
Gray's code

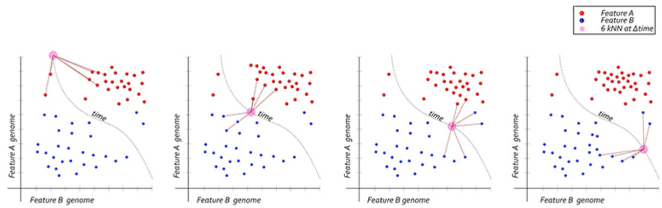


Figure 7
KNN data point at different instance (time) in the same data set

K-NEAREST NEIGHBOUR(KNN) MACHINE LEARNING

Since most of the space filling logics map multidimensional values to 1D/2D parameters, there is a need for continuous classification and order to optimize the space colonization.The K-Nearest Neighbors (KNN; figure 7) is one of the simplest algorithms used in Machine Learning for regression and classification problems[10]. KNN algorithms use data and classify new data points based on similarity measures (e.g. distance function). Classification is done by a majority vote to its neighbors. The data is assigned to the class which has the nearest neighbors. As you increase the number of nearest neighbors, the value of k, accuracy might increase [10].

EXPERIMENTS

The proposed method here makes use of the KNN algorithm to find the most optimized space filling curve in a given volume. The features of the optimization are based on cell size and curve length to accelerate the rate of machining without losing contact with the material for ISF. This paper can be considered as proof of concept to the field of ISF where lead over time and surface structure are optimized based on purely geometrical data from the workpiece. There were two sets of experiments performed where in the first experiment the global shape was predefined and the toolpath was optimised for machining, while in the second experiment, the shortest tool path was generated in a 2D space and overlaid to generate a 3D surface to be incrementally formed as the workpiece.

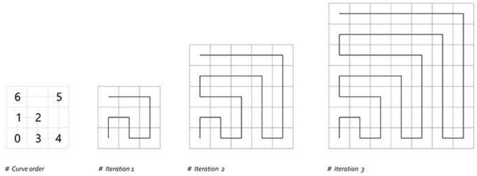


Figure 8
Radial logic for Procedural Space filling curve

Figure 9
Micro textured gills of mushroom supporting the cap

EXPERIMENT 1

In the first study case Nyuntm, the procedural system was used to design a self standing structure consisting of 105 unique panels fabricated using ISF (figure 8). Here the ISF process was carried out using multi-layered step downs and a radial space filling logic was applied from highest point bearing cell to the lowest.

To achieve a clean interpolated motion for machining, the sharp edges are replaced with filleted corners to arc like segments to avoid vibration on the sheet metal while in plastic state. The curves generated through the algorithm pass through a cell with the most minimum footprint. Similar to the formation of gills of a mushroom growth, the generated toolpath creates micro-texturing onto the final surface (figure 9) giving it local stiffness to achieve doubly curved forming (further see figures 10 and 11).

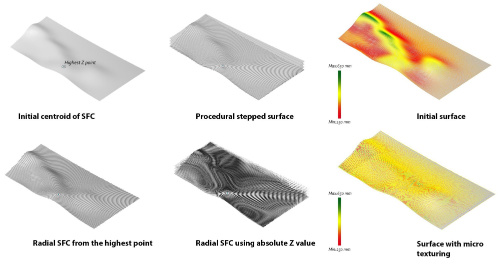


Figure 10
SFC generation and Mean Curvature analysis of a generic panel

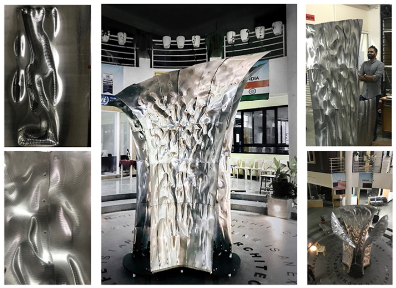


Figure 11
Final results of the pavillion fabricated using Procedural algorithms and ISF

EXPERIMENT 2

In the second experiment Force From, a simple snake scan curve (figure 12) is generated in a 2D region and then rotates / deforms the grid of cells to allow intersections, similar to a “Moire” pattern. The primary rule is related to the density of the pattern; where there are more intersection points the surface deformation is more drastic. This further defines the direction of where the deformation is happening in order

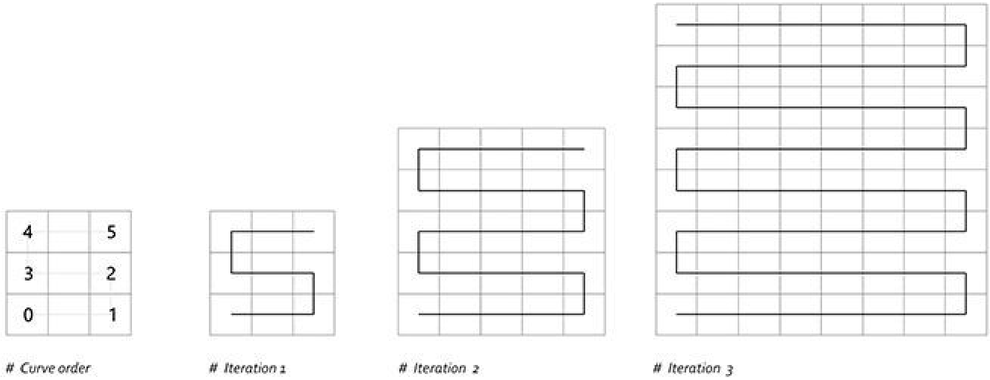


Figure 12
Snake scan logic for Procedural Space filling curve

to guide it to the desired direction. Using parametric software, a secondary set of rules was defined to create a variety of Moiré patterns that would later be used to generate a 3D surface (figure 13).

The data set for the kNN algorithm in this experiment floats between the intersection of two features ; Number of Intersection points on the curves and the region of intersection causing the surface deformation in Z axis.The K value in this case is tuned with the maximum depth achieved by ISF with the minimum curve length. As compared to conventional ISF toolpath which are concentric, the procedural method had produced more depth per area.

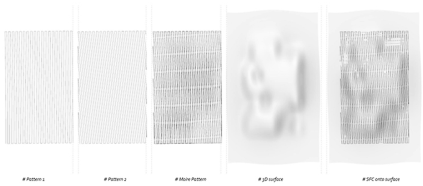


Figure 13
SFC logic to create 3D surface

CONCLUSION AND DISCUSSION

An established way to employ space filling algorithms is to produce precise and predictable models, which geometrically match digital models.In mass construction, even if certain parts or configurations are parametrically customized as digital models, to achieve true variation from object to object is not a straightforward task.We acknowledge the time consuming limitation of the ISF process to form sheet metal but by using space filling algorithms in a supervised learning environment, we can try to address this limitation in a novel way to gain lead over time in large production setup and in turn economically constructive.

Concurrently, designing texture often lies on the margins of the design process, it is rarely articulated for anything beyond purely visual effect.In this particular case it performs surface structuring through micro texturing as an added value.However it can be argued that the toolpath generated and the sheet metal formed are located in a space of convergence of material deformation and digital logics, which makes texture into a suitable problem for digital fabrication.These tests have been limited to geometrical extrapolation of data for optimization but we intend

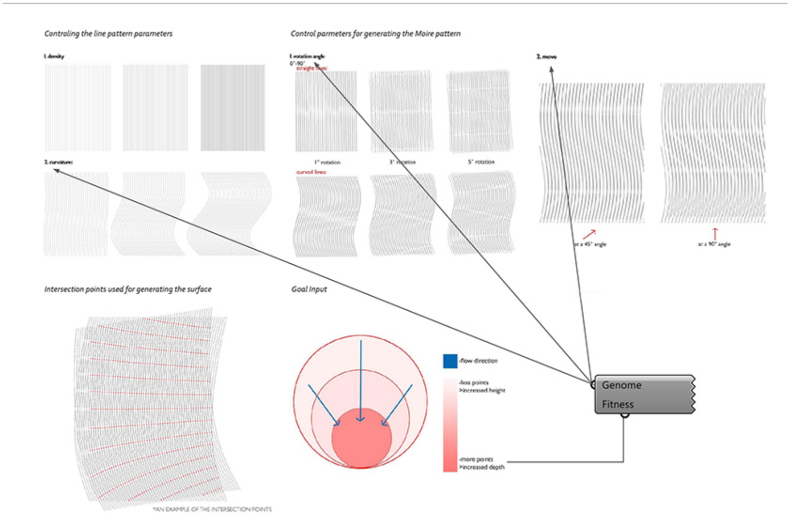


Figure 14
Optimization parameters - IAAC MRAC 2019-20 - Workshop 1.1

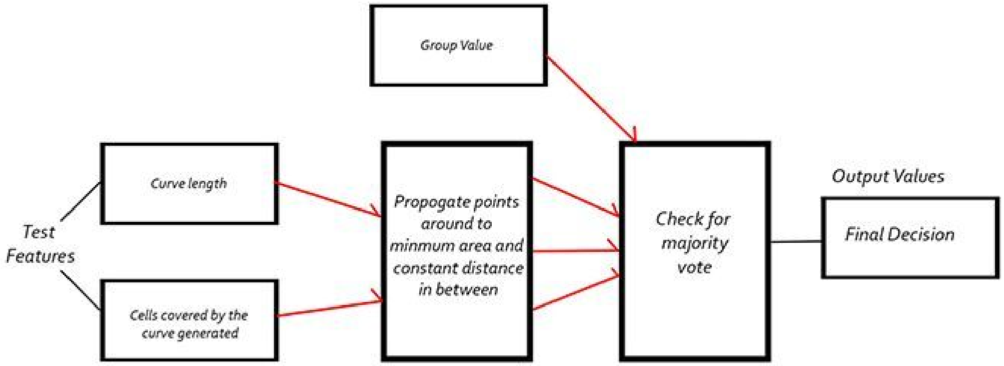


Figure 15
Schematic block diagram showing KNN optimization structure

to introduce sensors to have material feedback to be able to train the algorithm for accurate prediction.

AKNOWLEDGEMENT
Nyuntm - is a project of IAAC which was developed as a part of IAAC Global Summer School (India node) in 2019 developed by Kunaljit Chadha,Chirag Rangholia,Deva Prasad,Swapnil Gawande,Vinay Khare ,Soroush Garivani and participants.Force-Form- is a project of IAAC which was developed as a workshop for Masters in Robotics and Construction at IAAC in 2019 developed by Laura Puigpinos, Kunaljit Chadha,Hazal Yilmaz ,Ashkan Foroughi and students of MRAC 2019-20

Figure 16
Final results

REFERENCES

[5]Voorhies, D 1991, 'Space-Filling Curves and a Measure of Coherence', *Graphic Gems*, 2, pp. 26-30

[3] Castañeda, E 2015, 'Free-form architectural envelopes: Digital processes opportunities of industrial production at a reasonable price', *Journal of Facade Design and Engineering*, 3, pp. 1-13

[7] Fan, J, Yeo, WH, Su, Y, Hattori, Y, Lee, W, Jung, S, Zhang, Y, Liu, Z, Cheng, H, Falgout, L, Bajema, M, Coleman, T, Gregoire, D, Larsen, R, Huang, Y and Rogers, J 2014, 'Fractal design concepts for stretchable electronics', *Nature communications*, 5, p. 3266

[6] Gupta, S and Munjal, M 2014, 'Advanced Level Cyclic Gray Codes with Application Meenakshi', *International Journal of Electronics Communication and Computer Technology*, 4, pp. 619-622

[2] Jeswiet, J, Micari, F, Hirt, G, Bramley, A, Duflou, J and Allwood, J 2005, 'Asymmetric Single Point Incremental Forming of Sheet Metal', *CIRP Annals - Manufacturing Technology*, 54, pp. 88-114

[1] Leszak, E 1967, 'Apparatus and process for incremental dieless forming', -, -, p. -

[12] Leung, N 2018, 'Developing Space-Filling Fractals', -, -, p. -

[4] Mokbel, M, Aref, W and Kamel, I 2003, 'Analysis of Multi-Dimensional Space-Filling Curves', *GeoInformatica*, 7, pp. 179-209

[11] Potapov, D 2019, 'Multidimensional data structures usage in adaptive data storages', *Journal of Physics: Conference Series*, 1202, p. 012020

[8] Schrack, G and Stocco, L 2015, 'Generation of Spatial Orders and Space-Filling Curves', *IEEE transactions on image processing : a publication of the IEEE Signal Processing Society*, 24, pp. 1791 -

[9] Sieranoja, S 2015, 'High dimensional kNN-graph construction using space filling curves', ., ., p. .

[10] Singh, V 2018, 'Introduction To Machine Learning K-Nearest Neighbors (KNN) Algorithm In Python', -, -, p. -