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Reviewed Paper

DEVELOPMENT OF A NOVEL TEST ARTEFACT FOR CONFORMAL MATERIAL EXTRUSION PRINTING

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Abstract

Additive manufacturing (AM) allows for free complexity. However, the layer-by-layer manufacturing method traditionally relies on a G-code input to the machine, representing 2D planar slices of each layer, which eventually combines to represent the net-shape 3D geometry. Through modification of existing slicer software, thus modifying the G-code input to the machine, non-planar (conformal) shells can be generated on top of a traditional planar scaffolding. The objective of this work is to design a novel test artifact to aid in the creation of design rules and to identify machine limitations for conformal printing. With the use of non-conventional design features using trigonometric (sine) surfaces, this test artifact would allow for deeper insights into the print quality of organic shapes made possible using a commercial, low-cost, material extrusion 3D printer. It would also enable the creation of design rules for conformal printing to push forward the true dual-Design for Additive Manufacturing (dual-DfAM) potential.

Keywords: *Conformal printing, test artifact, dual-DfAM, material extrusion, parametric design*

1. Introduction

Additive Manufacturing (AM) processes offer many design advantages and opportunities compared to traditional manufacturing processes. AM offers free complexity and one of its main components is shape complexity, indicating that AM can create geometrically complex shapes. However, in Material Extrusion (ME), there are issues with surface finish along organic curves as a result of the stair-stepping effect. However, non-planar ME printing can account for these issues and increase the shape complexity opportunities within desktop ME machines.

Unlike traditional manufacturing techniques, Additive Manufacturing works by adding material layer by layer. By varying how each layer is printed very complex geometries can be created. For ME printing this is done by having a print head melt and then extrude out the plastic in the desired pattern [1]. However, there are some limitations that occur during slicing a geometry layerwise. For example, as seen in **Figure 1,** when software is used to create the slices there is some information that is lost. In the figure this shows up as the staircase effect.

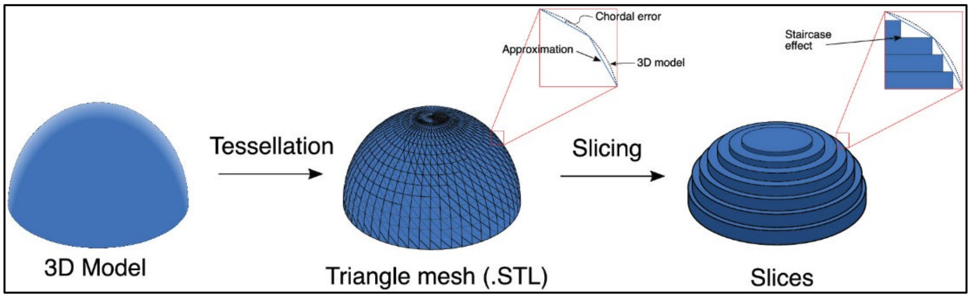

Figure 1*: Traditional method of generating planar slices from CAD* [1]

There are solutions to mitigate this problem which include decreasing the layer height, post-processing the part using acetone vapor smoothing, or using conformal printing. However, decreasing the layer height adds to the total build time and does not eliminate staircasing effect for high curvature geometries. Using post-processing steps leads to added costs as well as the need to compensate for the material that is smoothed during the operation.

Several researchers have presented the use of conformal printing for various applications. Adams et al. [2] fabricated electrically small antenna on three dimensional surfaces using conformal printing. Aerosol jet printing has been utilized to fabricate conformal layers for applications in electronics packaging [3][4], thermoelectric devices [5], antenna [6], and sensors [7]. Shembekar et al. [8], [9] have also developed and optimized trajectories for conformal printing for robotic arms to enable large scale printing. However, most of these studies were performed using complex equipment or large-scale applications.

Most of the complete and implemental research done on non-planar printing using desktop ME 3D printers was done by Daniel Ahlers' master thesis [10]. The research focuses on generating G-code for conformal printing layers while accounting for various machine-nozzle configurations. The output of this research provides a modified version of Slic3r, a free slicing software, that allows user-friendly access to the necessary parameters required to create a successful print. As shown in **Figure 2**, the modified version of Slic3r also shows the user the parts of the print which will be printed using conformal layers, shown in the pink with the planar layers shown in yellow.

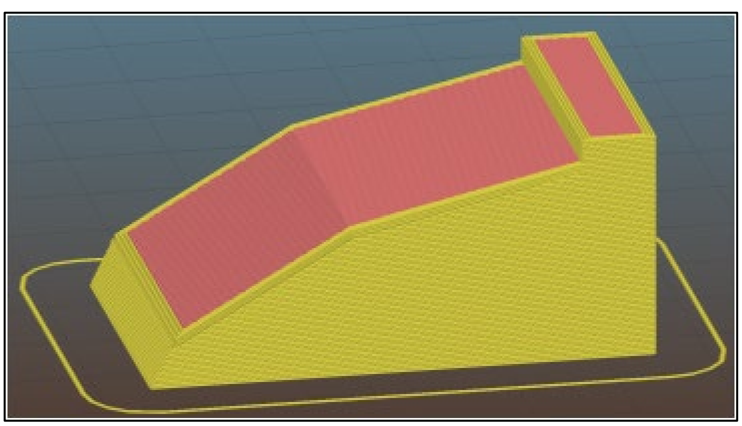

Figure 2: *Example of an output from the Slic3r modification for non-planar slicing* [10]

The nozzle geometry is a critical parameter and must be measured for the input to the slicer to allow it to generate the correct G-code. The important geometry of the nozzle is the nozzle height and nozzle angle as shown in **Figure 3.**

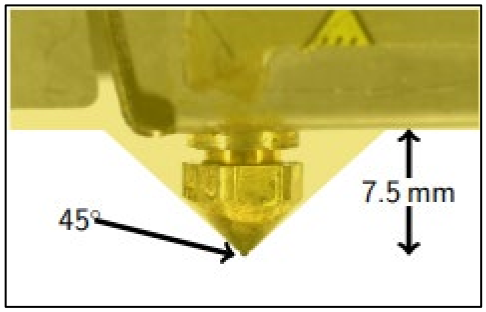

Figure 3: *Illustration of two critical parameters from a commercial desktop material extrusion 3D printer while generating non-planar layers* [10]

These dimensions are important as the angle of the nozzle and the height of the nozzle determines how steep of an angle the non-planar part can be before the nozzle collides with the previous layer.

Another potential solution to enable conformal printing using desktop 3D printer modification was presented by Hong et al. [11]. They proposed a method for the modification of a Prusa i3 to allow 5-axis 3D printing. An example of this setup can be seen in **Figure 4.**

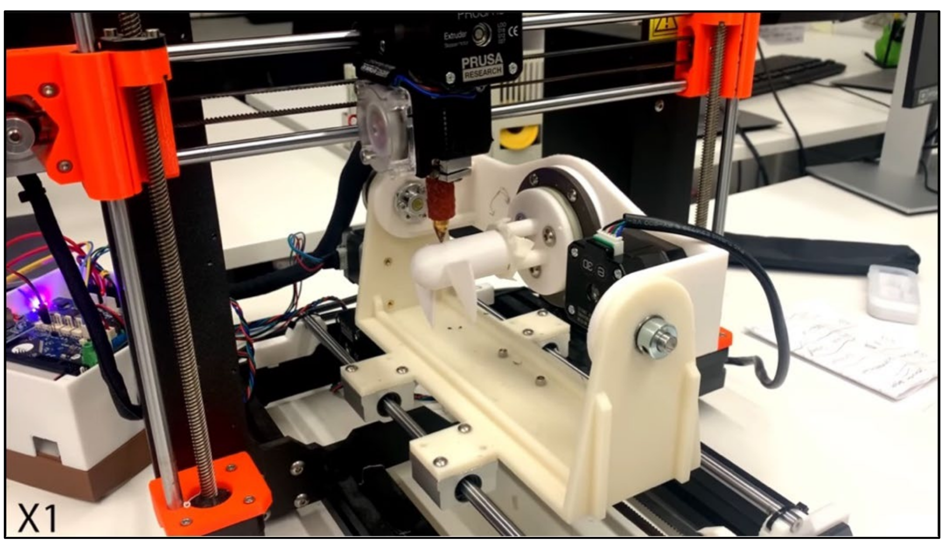

Figure 4: *Example of Prusa i3 modification for 5-axis printing* [11]

As can be seen from the different examples of conformal printing the designer has more variables that they need to consider when first creating a part and when preparing the part for printing. As listed above, the main variables that need to be considered are the dimensions of the nozzle on the printer and the overall geometry of what is printed. The geometry of the part needs to be designed such that it takes advantage of conformal printing, smooth surface finish, stronger parts, and provides an avenue for opportunistic DfAM features.

In previous work, researchers at the National Institute of Standards and Technology (NIST) created a test artifact to evaluate how well a specific metal AM machine can handle various kinds of design features [12]. As seen in **Figure 5** below, the test artifact includes a large variety of design features. There are holes and pins that test both repetition and minimum feature size. There are also “staircases” and a ramp to test other features that are commonly seen in metal AM parts. Each feature can be quantitatively measured to easily identify how well the machine has produced them. Each of these features falls under the category of restrictive Design for Additive Manufacturing (DfAM). If a machine cannot complete a certain feature, then limits can be set for future design of parts. Knowing these limits before building an important part is very valuable. There is a lot of room for future work in this area, in creating test artifacts for other AM processes outside of metal AM.

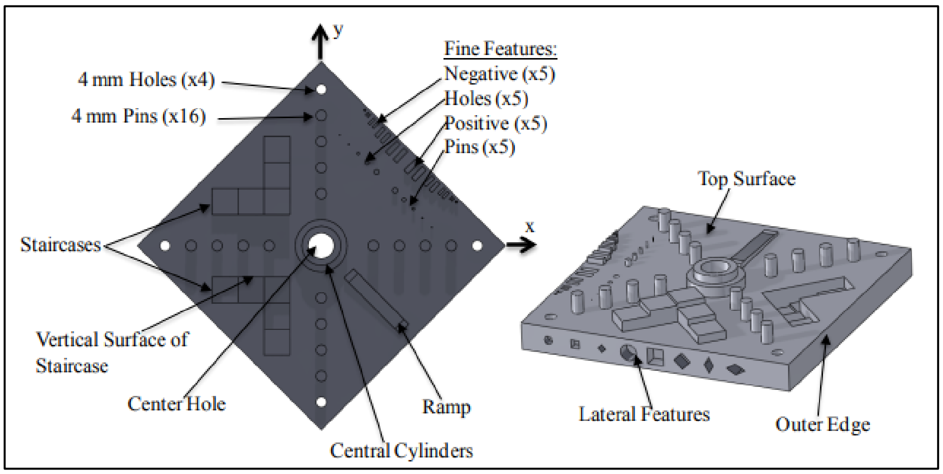

Figure 5: *NIST specimen; The most popular standard AM test artifact* [12]

The objective of this paper is to propose a novel test artifact design for conformal printing. This artifact contains contemporary parametric design features to mathematically represent and control the freeform geometry of non-planar surfaces. Section 2 expands on preliminary research conducted using a sample geometry. Section 3 highlights the fundamental parametric design features and the proposed test artifact design. Section 4 discusses the potential design of experiments and analysis for the proposed test artifact design.

2. Preliminary Experimentation

To understand the working of the Slic3r modification, a virtual machine was installed to run Ubuntu, the preferred environment to compile the graphical user interface (GUI) of the Slice3r modification. The GUI contained a separate section for activating non-planar slicing. The parameters along with their interpretations have been summarized in **Table 1**.

Table 1: Table showing the list of user controllable parameters using Slic3r modified conformal slicing tool [10]

Parameter	***Interpretation***
Maximum nonplanar angle	Sets the maximum angle where the surfaces are printed nonplanar
Maximum nonplanar collision angle	The maximum angle that can be printed without collision. This is only used for collision checking. The setting depends on the printer. 90° Disables collision checking
Minimum nonplanar area	Throws away all regions that are smaller than this to avoid very small nonplanar areas. Depends on the printed model.
Maximum nonplanar collision height	Sets the maximum height of nonplanar surfaces. Maximum nonplanar collision angle must be collision free in this region. The also depends on the hardware you use. Set to 999999 to disable.
Ignore collision size	Ignores collisions smaller than this value. Basically, a workaround to get rid of small artifacts generated by the offsetting algorithm that is used for collision checking.

Using the parameters in a stock Prusa i3MKS printer, a half dome with a diameter of 1.5 inches and a height of 0.25 inches was sliced using the non-planar slicing settings. The maximum height was set at 7.5 mm and the maximum angle was set at 45°. One of the major challenges we faced was that the probe for the auto-bed leveling sensor was obstructing the part geometry during the non-planar layers' printing. Thus, a stock Prusa mini was chosen for testing purposes. The half dome was printed using standard PLA 1.75 mm diameter filament with a 0.4 mm nozzle maintained at 215°C, while the bed temperature was maintained at 60°C. The total print time was 5 minutes 13 seconds. The final printed part can be seen in **Figure 6**.

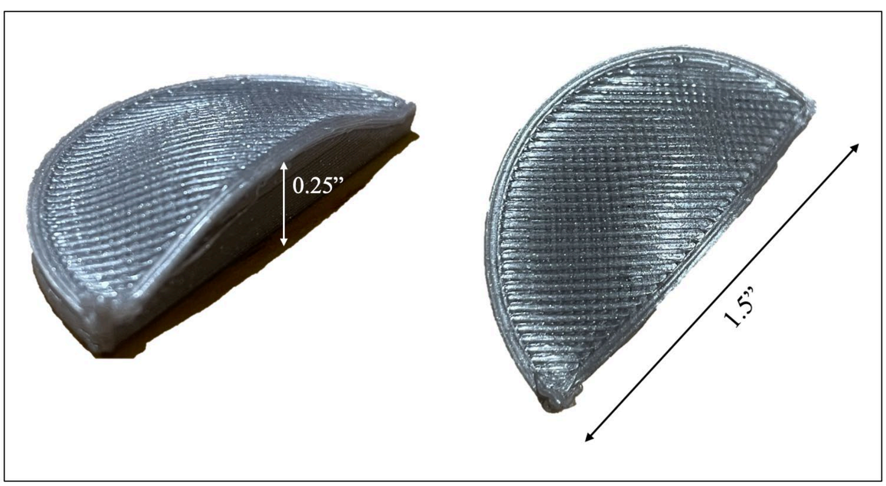

Figure 6: *The test half-domes printed using conformal layers on the Prusa mini*

The first learning was that the non-planar layers were printed on top of a planar base. The slicer generated planar layers to approximate the geometry and then printed the last few layers of the shells using non-planar material deposition. Additionally, it was noted that there was filament accumulation at the corner where the non-planar deposition started and ended between layers. Overall, it was observed that the final quality was visually more appealing as compared with the standard planar slicing. The conformal layers resulted in a much smoother surface.

It is also important to note that these tests were performed using a stock Prusa mini printer. There are several nozzle modifications available to increase the clearance between the nozzle and the extruder to increase the "maximum non-planar height" and "maximum non-planar angle" parameters that allow for varied regions of conformal slicing. One such modification by "nonplanar.xyz" [13] can be seen in **Figure 7**.

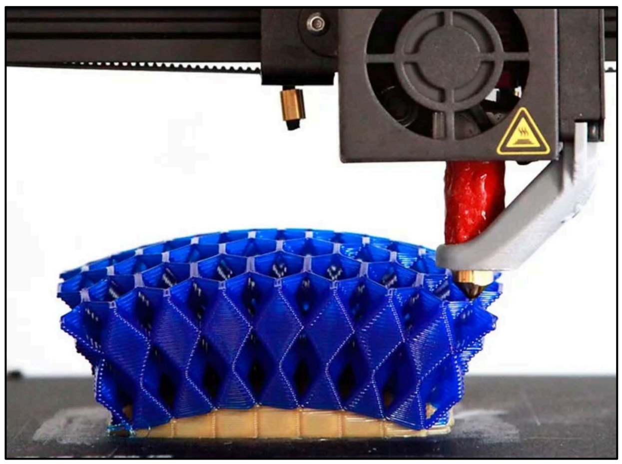

Figure 7: *Example of nozzle modification to enhance non-planar printability* [13]

3. Parametric Design of Specimen

Due to the various range of variables available for assessing the functionality of a designed non-planar specimen, different approaches were considered for parametric representation of variables. The initial phase of the design began by defining different parameters related to non-planar slicing of the final specimen that have the highest potential of assessing the accuracy of the printing process. These parameters are considered based on existing literature and were divided into three different sub-categories. As shown in **Figure 8,** the parametric ribbon (sinusoidal) will focus on the highest and lowest points to reach in a non-planar scenario without failure. The variables are defined in a 2D interface based on a gradually changing sine function, and the dimensions of the final specimen can be modified as well. It is worth mentioning that the parametric workflow will give the designers and engineers the opportunity to adjust the design variables interactively based on specific characteristics of AM manufacturability. In general, based on a printer's assembly and requirements, the final geometry can be altered. The second part of **Figure 8,** focused on gradually changing the curvature in 3D space. By focusing on freeform hyperbolic form, the end effector's range of motion for printing a double curvature geometry is investigated. The hyperbolic form is designed parametrically using Python coding and changing the variables will generate a variety of forms. The final range of variables is included in designing a two-curvature dome-shape geometry**.** The variables will generate a sub-specimen with gradual changing of curvature in a 3D space sing force density form-finding method. The final geometry will assess the possibility of double-curvature printing in a more controlled environment. By changing the parameters related to the form finding process, the highest peak point can be determined to assess non-planner criteria.

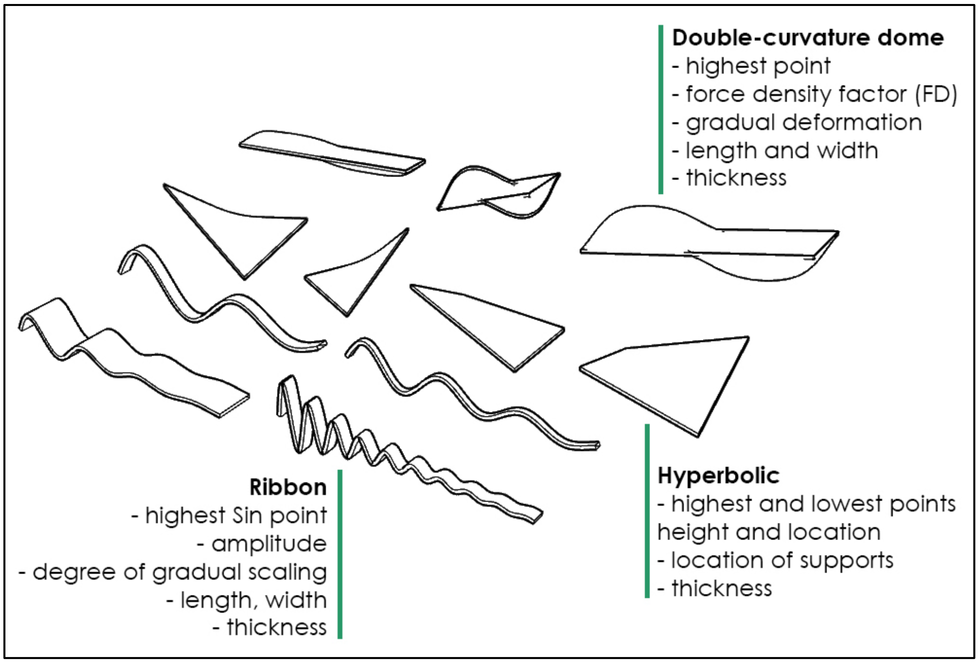

Figure 8: *Different parametric prototypes using Rhino/Grasshopper*

Focusing on the three different parametric geometries, a final 'parametric workflow' was defined to generate the needed specimen. The workflow was based on the initial sinusoidal function that gives the designer the opportunity to change amplitude and frequency to generate design alternatives. By gradual change of height to the base of the specimen, mountain and valley-like series of shapes was extracted. The geometry was blended to provide a baseplate for printing and the final geometry was exported as an STL file. **Figure 9** illustrates the range of variables including thickness of each part. For the proposed test artifact design, nine different case studies are generated by a combination of amplitude and frequency in low, medium, and high settings for a full factorial design. The final geometry can be replicated as many times as needed to perform accurate data-based printed design analysis. As shown in **Figure 9**, different models can be merged to generate a single specimen ready to perform the slicing process. Having low, medium, and high settings will provide a reach dataset to assess the importance of frequency and amplitude of initial sine function on slicing and actual printing process.

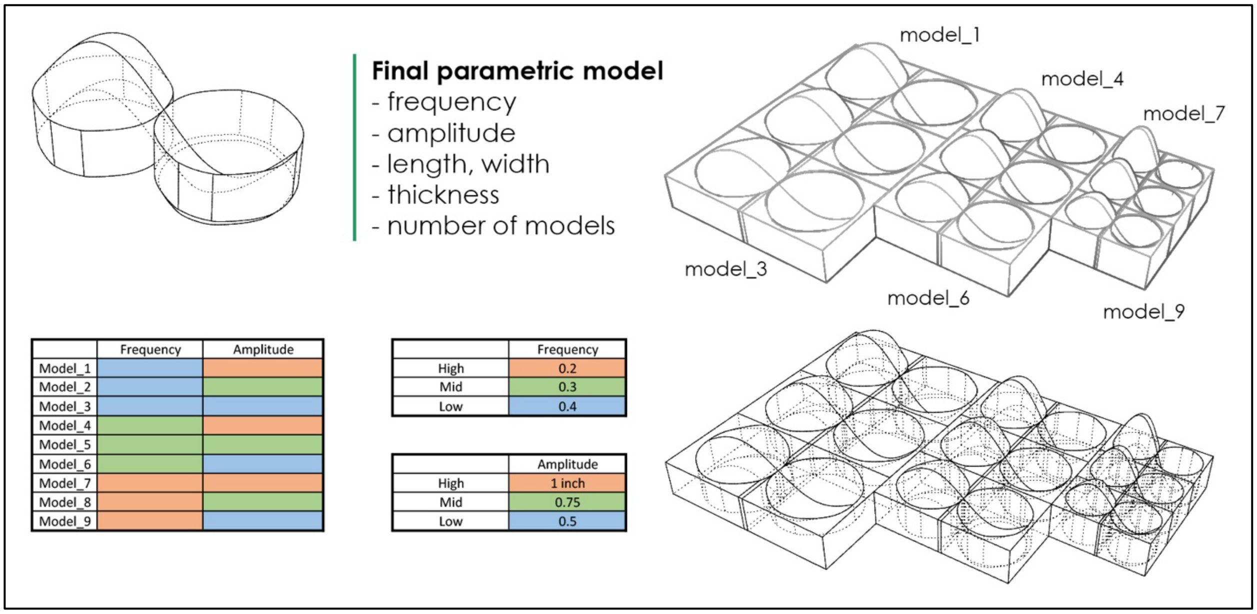

Figure 9: *Final prototype of the proposed test artifact with variables related to parametric workflow*

4. Design of Experiments for Conformal Test Artifact

Using the learnings from the preliminary experimentation, and the proposed specimen design, the proposed design of experiments contains the full factorial analysis of two design variables varying over three levels. To identify the limit of generating conformal layers, the Slic3r modification GUI was used. However, to include a more comprehensive analysis it is proposed that the conformal sliced printed geometry must be compared to the planar sliced printed geometry. Both parts will be printed using the same layer thickness using three replicates per slicing method to account for variation. Post-printing, the parts will be 3D scanned using the LiDAR scanners present in a modern-day smartphone. The failure criteria would be guided by the root mean square (RMS) surface deviation between the measured data (3D point cloud obtained using the 3D scanner app), and the CAD surface data. Such analysis can be done using the advanced inspection software Geomagic Control X by 3D Systems. The RMS difference would account for a surface averaged quantifiable measure of surface quality. If the RMS difference between the measured and design data is within 10% of the layer thickness, it will be considered a pass, otherwise, it will be declared a failure point. The failure point will be used to identify areas where conformal printing would be beneficial.

The results obtained from Slic3r using non-planar settings for the parametric features as well as the final test artifact have been shown in **Figure 10** and **Figure 11** respectively. The non-planar regions can be seen in pink whereas the planar regions are represented in yellow. It was also observed that by changing the nozzle configurations, different regions of conformal printing were possible. It was interesting to note that in the test artifact, there were substantially low non-planar layers generated within the negative sinusoidal features. This was attributed to the low "maximum nozzle height" parameter which makes it difficult to print depressions while being able to print peaks. It was observed that low amplitudes tend to be easier to fabricate using the stock hardware in desktop 3D printers. It was also noted that lower frequencies tend to be favored while using non-planar printing.

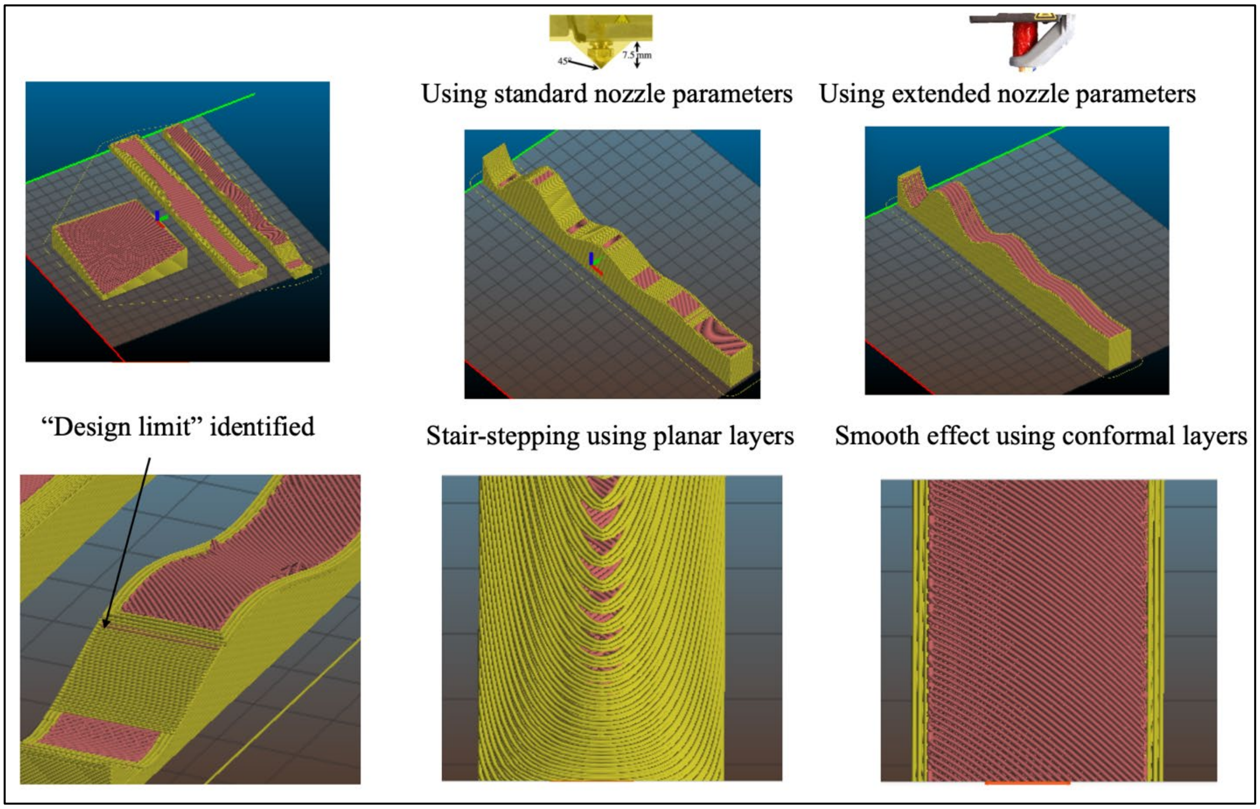

Figure 10: *The different parametric features sliced using planar and non-planar slicing*

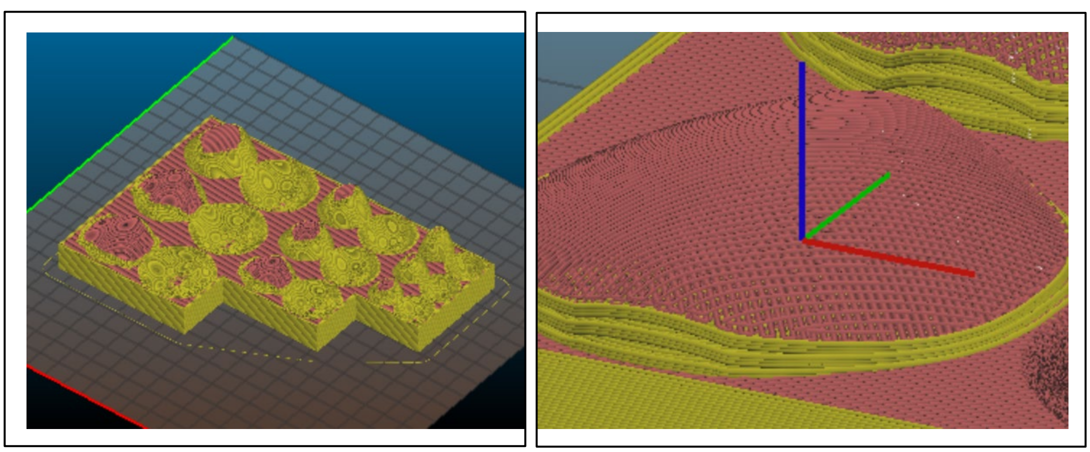

Figure 11: *The proposed test specimen design sliced using non-planar slicing (left); Close up of the non-planar layers (right)*

5. Conclusion

This paper proposed a novel test artifact design for conformal printing. The designing process contained parametric design features such as sinusoidal, hyperbolic, and double curvature surfaces that represent a contemporary approach to rethinking design features for organic looking geometry possible using AM. The final test artifact contained two design variables – amplitude, and frequency, at 3-levels for a full factorial design. The test artifact was sliced using the non-planar settings within the Slic3r modified GUI using printer parameters for a stock material extrusion desktop 3D printer. It was proposed that three replicates of the test artifact be printed using planar and non-planar techniques. These parts would be compared on the basis of RMS surface deviation between measured geometry and as-designed geometry using Geomagic Control X. Additionally, the limits of generating non-planar layers using the traditional desktop 3D printer would be identifiable from the slicer using multiple machine-nozzle configurations.

The overall objective of this study is to answer the question, "If it can be printed conformally, does it mean we should print it?" The conformal layers require a planar set of layers to create a base upon which it adds conformal layers. Right now, these planar layers represent solid material, but it could be modified to represent removable support material which would provide avenues for generating freeform "shell" geometries that could be used for potential applications where surface quality is of utmost importance (e.g. injection molding, conformal cooling channels). However, surface quality can further be enhanced using post-processing steps such as acetone vapor treatment for PLA parts. It is possible that future studies might show enhancement in cycle times and quality for such post processing methods using conformal layers. Authors are currently continuing experimental investigations into qualitative and quantitative comparisons between the test artifact printed both using planar and conformal slicing. Limitations of this study include the use of only the existing Slic3r modification software to generate planar layers, comparing design limits at three levels using two non-conventional design features. The work remains conceptual at this stage with future work being the fabrication of the test artifact using stock, and modified nozzles. The future work also includes the addition of a wider range of parametric design features to expand the possibilities using conformal printing.

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References

[1] G. A. Nisja, A. Cao, and C. Gao, "Short review of nonplanar fused deposition modeling printing," *Mater. Des. Process. Commun.*, vol. 3, no. 4, p. e221, Aug. 2021.

[2] J. J. Adams *et al.*, "Conformal Printing of Electrically Small Antennas on Three-Dimensional Surfaces," *Adv. Mater.*, vol. 23, no. 11, pp. 1335–1340, Mar. 2011.

[3] J. A. Paulsen, M. Renn, K. Christenson, and R. Plourde, "Printing conformal electronics on 3D structures with aerosol jet technology," in *FIIW 2012 - 2012 Future of Instrumentation International Workshop Proceedings*, 2012, pp. 47–50.

[4] A. A. Gupta, A. Bolduc, S. G. Cloutier, and R. Izquierdo, “Aerosol Jet Printing for printed electronics rapid prototyping,” in *Proceedings - IEEE International Symposium on Circuits and Systems*, 2016, vol. 2016-July, pp. 866–869.

[5] M. Saeidi-Javash, W. Kuang, C. Dun, and Y. Zhang, “3D Conformal Printing and Photonic Sintering of High-Performance Flexible Thermoelectric Films Using 2D Nanoplates,” *Adv. Funct. Mater.*, vol. 29, no. 35, p. 1901930, Aug. 2019.

[6] S. Y. Jun, A. Elibiary, B. Sanz-Izquierdo, L. Winchester, D. Bird, and A. McCleland, “3-D printing of conformal antennas for diversity wrist worn applications,” *IEEE Trans. Components, Packag. Manuf. Technol.*, vol. 8, no. 12, pp. 2227–2235, Dec. 2018.

[7] T. Blumenthal, V. Fratello, G. Nino, and K. Ritala, “Conformal printing of sensors on 3D and flexible surfaces using aerosol jet deposition,” in *Nanosensors, Biosensors, and Info-Tech Sensors and Systems 2013*, 2013, vol. 8691, p. 86910P.

[8] A. V. Shembekar, Y. J. Yoon, A. Kanyuck, and S. K. Gupta, “Generating robot trajectories for conformal three-dimensional printing using nonplanar layers,” *J. Comput. Inf. Sci. Eng.*, vol. 19, no. 3, Sep. 2019.

[9] A. V. Shembekar, Y. J. Yoon, A. Kanyuck, and S. K. Gupta, “Trajectory Planning for Conformal 3D Printing Using Non-Planar Layers,” 2018.

[10] D. Ahlers, F. Wasserfall, N. Hendrich, and J. Zhang, “3D printing of nonplanar layers for smooth surface generation,” in *IEEE International Conference on Automation Science and Engineering*, 2019, vol. 2019-August, pp. 1737–1743.

[11] F. Hong, S. Hodges, C. Myant, and D. Boyle, “Open5x: Accessible 5-axis 3D printing and conformal slicing,” *CHI Conf. Hum. Factors Comput. Syst. Ext. Abstr.*, pp. 1–6, Feb. 2022.

[12] S. Moylan, J. Slotwinski, A. Cooke, K. Jurrens, and M. A. Donmez, “An additive manufacturing test artifact,” *J. Res. Natl. Inst. Stand. Technol.*, vol. 119, pp. 429–459, 2014.

[13] “Non-planar | Nonplanar.xyz.” [Online]. Available: https://www.nonplanar.xyz/. [Accessed: 01-May-2022].