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Continuous Sculpting as a Novel Method to Reduce the Staircase Effect in Solidfreeform Fabrication Processes that are Dependent on Phase Transformation.

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Abstract

Inherent to 2-1/2 axis deposition in Solid Freeform Fabrication is Staircase effect. The surface geometry of parts produced using Solid Freeform Fabrication, therefore is not smooth. Continuous sculpting is a novel method that combines additive manufacturing to surface modification by relative motion of a forming tool. Molten material is added to substrate. A forming tool that can tilt along different axes is connected to the end effector. The forming tool is oriented along a desired angle and then applies force on the molten material to give it desired
shape on the fly. This paper introduces the novel method and a simple case studies.

Introduction

Past few decades have seen significant development in the field of solid free form fabrication. The developments have been done in field of processes, materials, and computer representation of the parts. However, inherent to the 3D printing is 2-/12 axis-based deposition that make parts susceptible to staircase effect[1,2]. Parts produced by such processes are limited in meeting functional intent or undergo significant post processing before they can be used. Parts manufactured by Solid Freeform Fabrication as it cannot be used for systems and assemblies that require sub millimeter order tolerances and part accuracy. Typically, the parts produced are primarily for the visualization and form fit evaluation or short duration functions. When features are critical, the staircase effects and a mismatch between the inter-layer thickness allowed by the SFF may lead to building the features partially. While such a problem may to certain extent be addressed by adaptive slicing; for the high-end parts especially the ones that are finish and feature form critical, may require significant pre- and post-processing.

Many multi-axis CNC systems, Robotics systems as well as hybrid CNC-Robot systems have been used to add material, have been proposed [3,4,5]. Alternatively, a hybrid additive-subtractive processes have been proposed for producing high quality useable parts [6]. The systems are, however, extremely complex and require operator subject matter expertise.

Most of the 3D printing platforms are based on a Cartesian architecture. Where displacement of end effector is performed along three cartesian axes and the material is extruded/added along one of the major axes. Usually, the axis of material addition is along the Z axis. Minimum resolutions within the form is dependent on stepper motor resolution and the linear actuator. Using the 3D printing, it is nearly impossible to produce a high-end functional part by only additive process. To meet the dimensional and material specifications, the subtractive processes must go hand in hand with the additive process.

Many other SFF dependent processes [7] such as development of scaffolds for use in cell-based therapies to repair damaged bone tissue cannot use subtractive post processing for form fit improvements therefore, the additive process must in first pass manufacturing minimize the staircase effects. The residue created from the scaffold may impact the bone tissue generation.

This paper describes an alternate approach being explored to reduce the staircase effect by mechanically forming semi-solid material before it is solidified. The paper describes the architecture of the test system and specifics of the equipment used. The paper also describes the preliminary findings and suggests a path forward to implementation.

Additive-subtractive process integration

The 2-1/2 axis deposition mode assumes that the material addition is such that each layer is deposited to enable a uniformly thick layer. Between two subsequent layers, geometrically there is no variation along the axial direction. As described in the Figure 1, any critical features lying within two

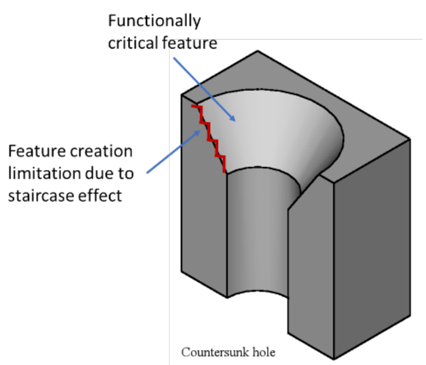

Figure 1: An example of functionally critical feature missed due to staircase effect

adjacent layers will be missed.

Another issue worth noticing is that at the fundamental level, the material is dispensed in non-square profile (Figure 1). This may be attributed to the surface forces/surface tension of the fused liquid. The uniformity of the layer surface profile is aggregate of material dispense along different regions of a

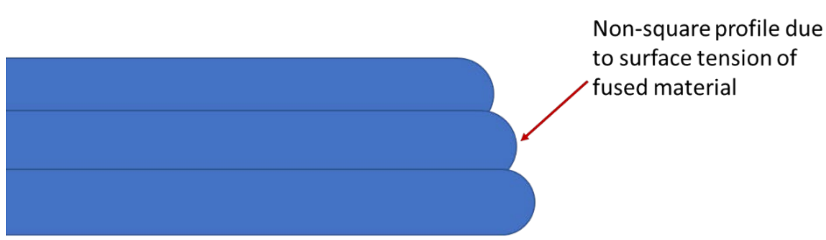

Figure 2 : Non-square profile along the outer surface of 2-1/2 axis deposition

layer.

Remelting of previously deposited material and mixing with the newly added material enhances the surface uniformity; however, there are many factors that limit the quality of the surface. The energy may not be sufficient to melt the previously deposited material adequately. The material properties may not be amenable to frequent remelting. Relying purely on the material fusion to ensure a flat surface makes it extremely difficult to quantify the extent of variation. For the additive processes the amount of material added depends on (1) the rate of material dispensing and (2) the relative speed of the additive end effector and the substrate.

Many SFF processes resort to the combination of additive and subtractive manufacturing operations to build superior quality functional parts. Material deposition and intermittent machining to (1) restore a datum for critical features (2) eliminate significant geometric variations (3) Add blind features (4) remove sacrificial material needed to support overhanging regions.
While many researchers have frequently used a complex architecture that is based off two spatial manipulators one additive and one subtractive, the same would not be advisable for the following reasons-

1. Multiple manipulators would need to establish corresponding multiple datum points. For a high quality part, a range of accessory implements and feedback transponders will be needed to minimize the system to system variation.
2. Two separate set of manufacturing data needs to be generated. While CNC code can incorporate not only linear but also many curvilinear, path segments the same for 3D printing is based on linear segments. The STL formatted file and subsequent manufacturing data produced from the STL file comprises of linear segments. It is possible to utilize the high resolution path traversal and therefore superior geometric attributes with the CNC codes,

Forming tool to reduce the staircase effect by continuous casting
Concept proposed in this paper suggests using an actuator to sculpt the deposited material before it is fully solidified. Figure 3 describes the process steps for continuous sculpting. A plunger is placed within proximity of the material deposition head. After a new layer of material is deposited the plunger is actuated. The plunger pushes the molten material to imprint form. Next the plunger is retracted, and the material is allowed to solidify.

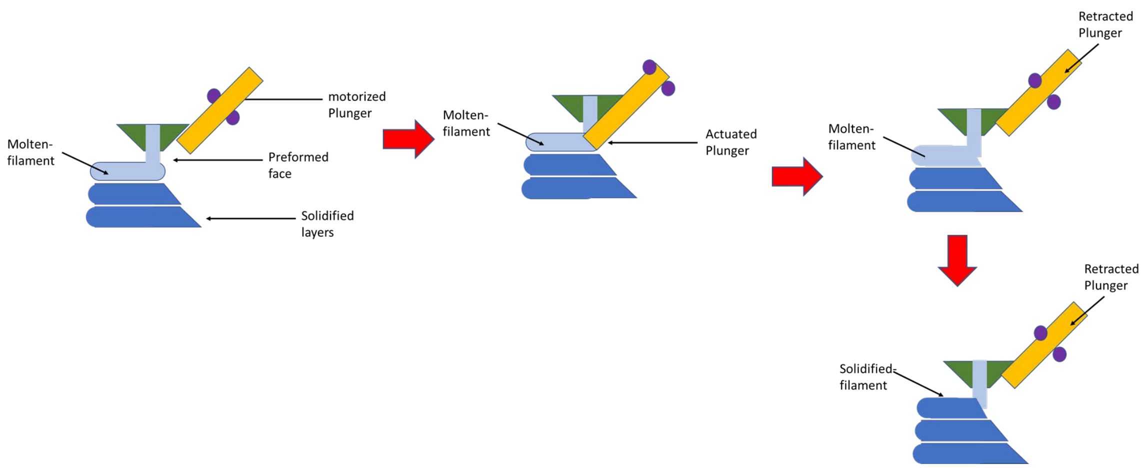

Figure 3 : Steps for continuous sculpting as a method to reduce staircase effect.

As described in the Figure 4, the angle of the plunger may be adjusted per the desired surface profile.

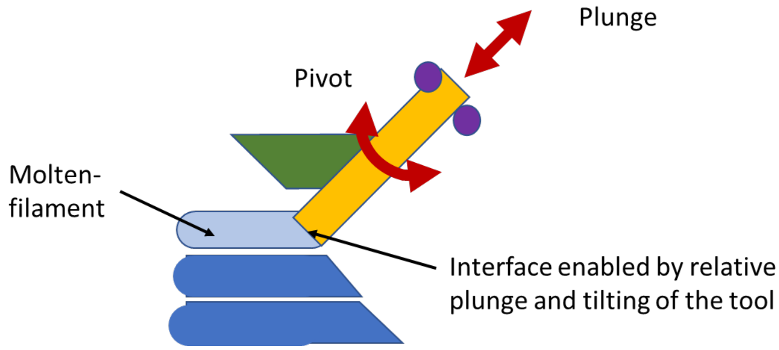

Figure 4 : Pivot and plunge of the tool to enable desired surface profile

The material delivery by extrusion and the path followed is a continuous process however, the plunging is done intermittently. The plunging action is required to separate the tool from molten material and prevent deformation due to adhesion of melted material onto the tool. The frequency of the plunging tool must enable overlap such the surface profile is smooth. As shown in Figure 5, if the plunger frequency is inadequate and does not allow overlap in the indentations the surface quality is impacted.

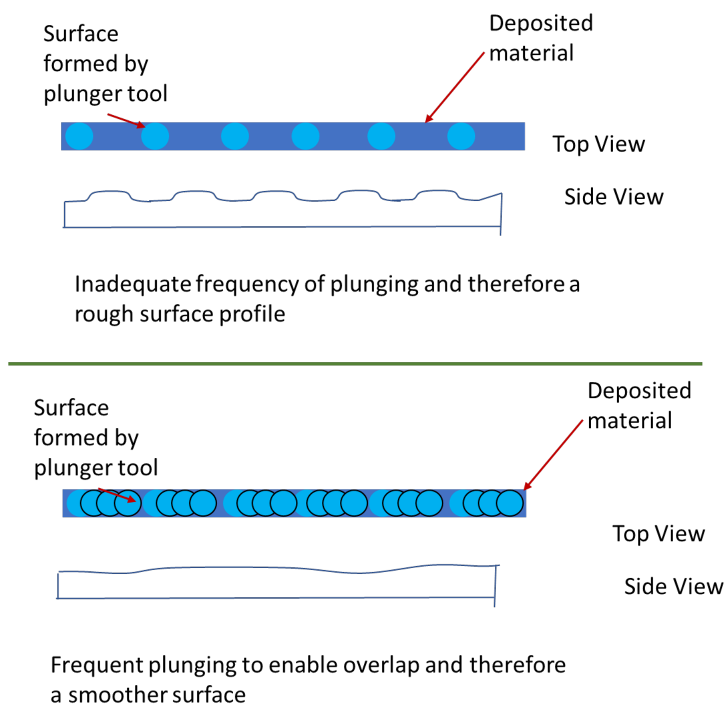

Figure 5: The impact of plunger frequency on the roughness of the surface profile

Prototype experimental equipment

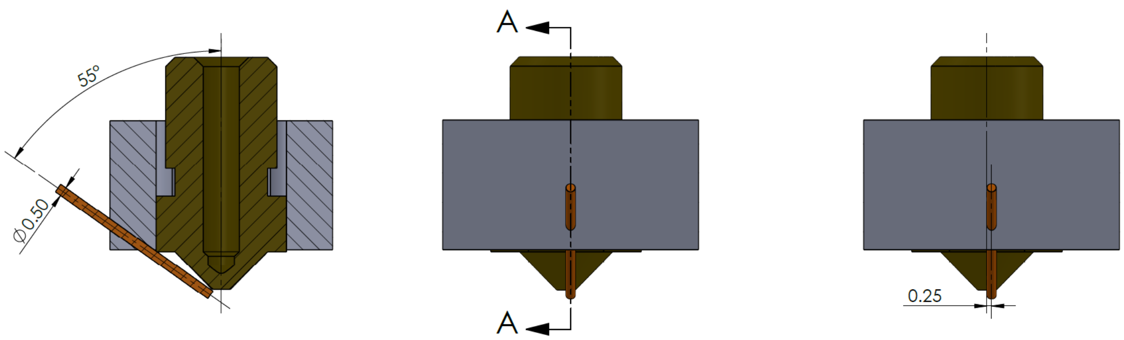

Figure 6 : Section view of modified end effector

The experimental setup is created by retrofitting a Creality Ender 3, PLA compatible 3D printer. As described in Figure 6, a shell is attached to the extruder with a hole to enable smooth passage of 0.5mm diameter stainless steel wire. The hole diameter for passing the wire is 0.6mm and the hole is drilled at 55degrees. Due to limitation of the available hardware the current setup has a fixed plunging angle.

The plunger hole is 0.25mm offset from the plane of extrusion. Allowed speed limit of printing for the end effector is 60-100mm/s. However, the experiments are performed at print speed of 75mm/sec. The extruded material is 1.75mm PLA.

Figure 7 describes the actuation mechanism. The actuation mechanism is built using a linear screw drive. The linear drive is activated by a 2-phase 4-wire 22.5 Degree Stepping Angle Stepper Motor FSM0815-KD95. The linear screw drive is based on a Screw Diameter 2.5mm and Screw Length of 43mm. For actuating the mechanism, itself a general purpose open source microcontroller, Arduino UNO is used. The driver for the motor is a L298 Stepper driver. During the deposition actual plunge frequency is 1/sec.

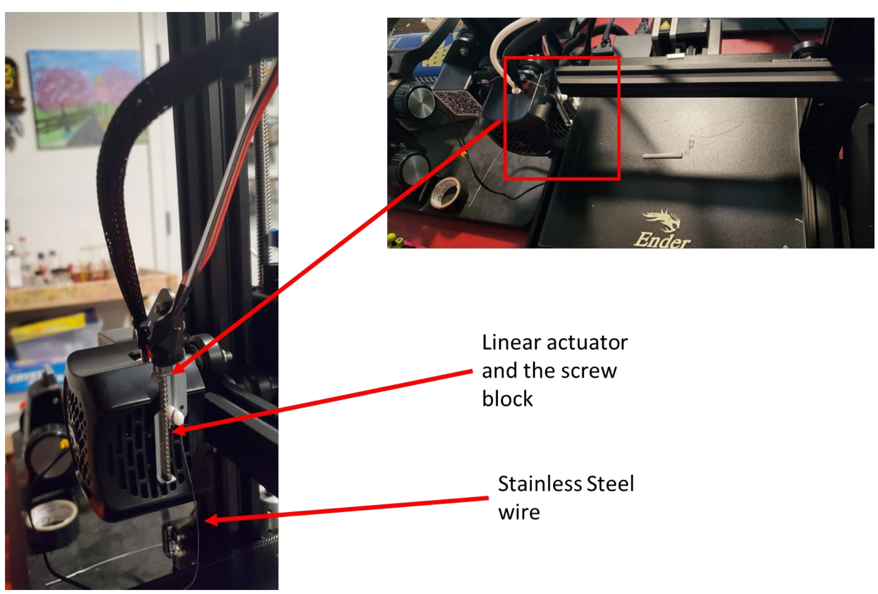

Figure 7: Actuation mechanism

Initial results and findings

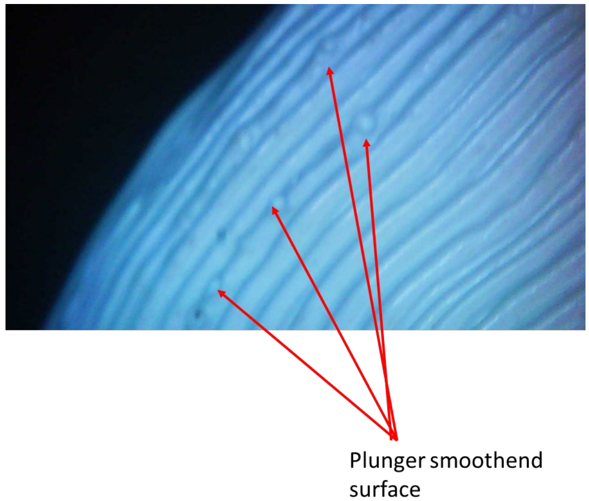

Figure 8 : Results from 1 plunge/sec

Figure 8 describes the surface smoothening by plunger actuation. The stepper motor-based mechanism limited the plunge frequency to create a smooth uniform surface. The 3D cad model of the part is created with surface over-compensated for the staircase effect.

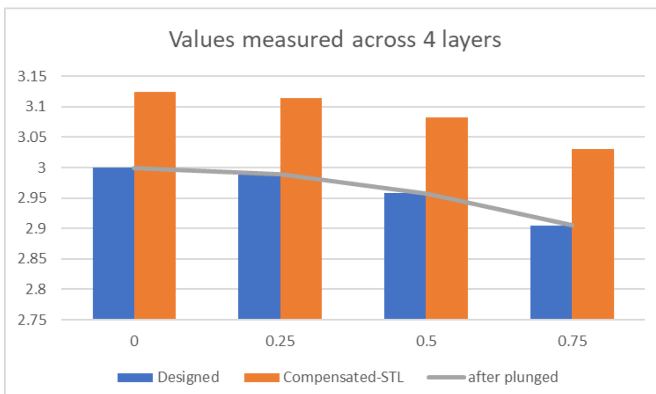

Figure 9 : measured values across 4 layers

Figure 9 shows measured values for 4 layers where the desired layer height of approximately 0.25mm, a compensation of 0.125mm was done for each layer. After the plunging the profile of the surfaces. As manufactured surface profile exhibits additional 0.125mm; however, the points along where the surface modification is done using the plunger the surface is in agreement with the desired surface profile.

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<u>Conclusion/Summary/ Future work</u>

A plunger-based continuous casting is done to improve surface profile of deposited layers. Preliminary results are described in the paper and exhibit improvement using continuous casting. Additional experiments and measurements are required to prove effectiveness of the approach. Other non-sticking material and improved plunger tool will be used to prevent adhesion of molten plastic and the tool. Plunger will be developed further to add tilting such that the tool can adapt to local surface inclination.

Resources:

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