3D Printing of Non-Planar Layers for Smooth Surface Generation

Colloquium - Master Thesis

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Outline

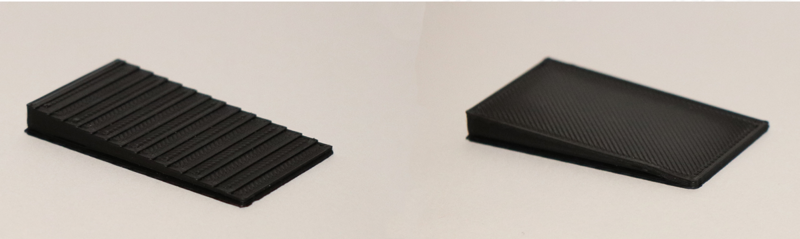
Motivation

- Important technique for rapid prototyping and small scale productions
- Can fabricate objects which are unable to produce with classical fabrication methods
- 3D printing covers wide variety of techniques
- Focus on standard FDM Printers
- Most printers slice object into discrete 2D layers
- Stacking layers onto each other to form 3D object
- Approximate 3D object
- Approximation errors from 3D object

Problem

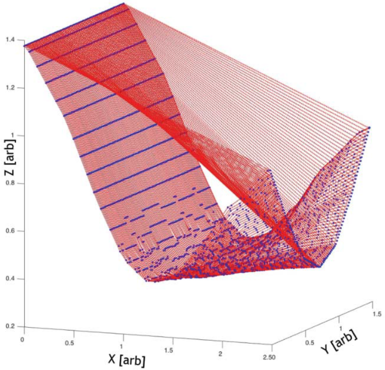
Stair stepping

- Especially on surfaces close to horizontal
- Unaesthetic
- Approximation errors from designed object
- Higher friction
- Aerodynamics are different
- Can be reduced by thinner layers
- Can be removed by post processing
- Or printing non-planar layers



Fully Three-dimensional Toolpath Generation for Point-based Additive Manufacturing Systems[1]

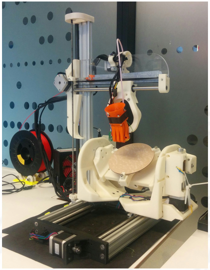
- Algorithm to create non horizontal toolpath
- Collision check with nozzle
- Inspired by cnc milling
- Tested on squared plane
- Extrusion is calculated by path length
- Just an path generation algorithm for a single plane
- No way to get to this shape from planar printbed
- No real prints where printed



[1]

5-axis 3D Printer[2]

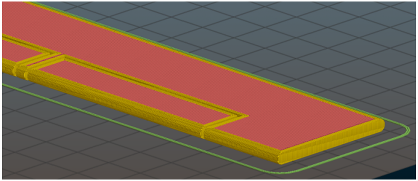
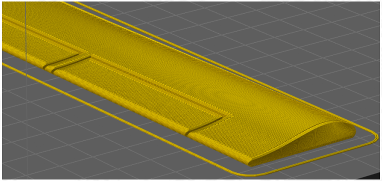
- Added a rotatable printbed to an FDM Printer
- Can print overhangs of 90°
- Tilting the bed and printing on previously printed material
- Toolpath is generated with a small java program
- Toolpath generation is only for simple shapes like spheres
- Has to be composed manually
- Not for individual objects
- Able to print objects with nonplanar layers



[2]

3D printing: Non-Planar Layer FDM[3]

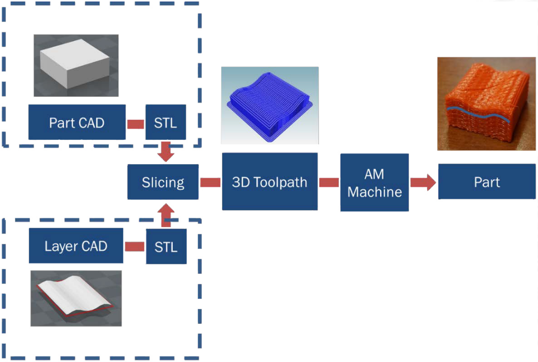
- Uses standard FDM printer to print non-planar layers
- Standard slicing software for toolpath generation
- Post process toolpath with script
- Changing height in path using waves or curves
- Splitting path up for curvy surfaces
- Only simple curves and waves possible
- Not following the surface of the object
- Does not change filament flow

[3]

Active-z printing: A New Approach to Increasing 3D Printed Part Strength[4]

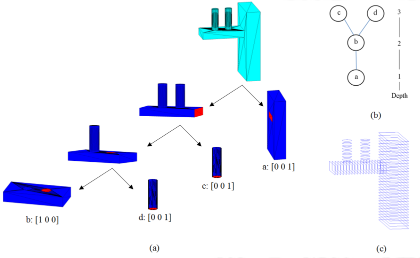
- Used non-planar layers to increase part strength
- Used bread slicer to get non-planar toolpaths.
- Non-planar toolpaths increase the strength of the part



[4]

Multi-direction Slicing of STL Models for Robotic Wire-feed Additive Manufacturing[5]

- Multi directional Slicing
- Model is decomposed in sub components
- Each subcomponent is sliced in one build direction
- Toolpaths are composed into one
- Needs printer with at least 4 DOF
- No actual objects printed

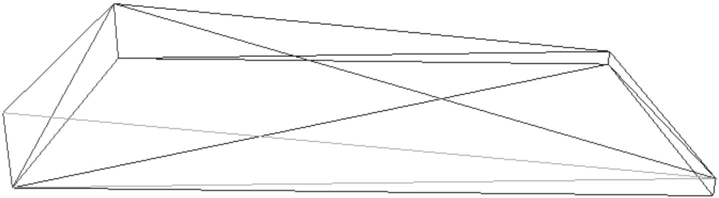


[5]

Model

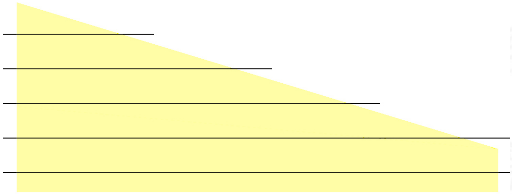
STL

- Defacto standard
- Many unconnected triangle facets
- Each triangle has three vertices and a surface normal
- Model has to be watertight
- Can be stored in either ASCII or Binary format.



Slicing in individual layers

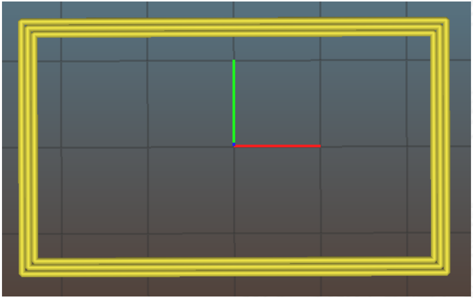
- Slicing height depends on configuration
- Each Layer gets 2D Polygons of the area where the model is cut
- Vertices of polygon are generated where the cut intersects with a triangle edge



Slicing

Generating perimeters

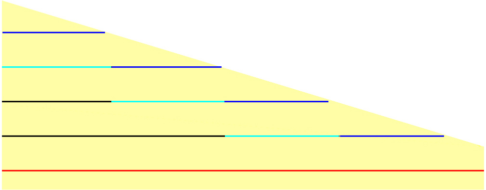
- Generated along the inside of the polygons
- Each generated path is a closed loop
- Number of loops is previously configured



Slicing

Identifying surface type

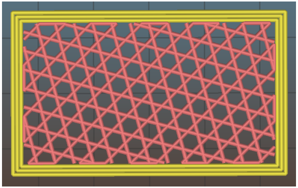
- Surfaces of the object are classified
- On first layer -> bottom
- Nothing on layer above -> top
- Nothing below but on higher layer -> overhang
- Bottom layer below or top above -> internal solid
- Everything else -> internal
- Each type is later handled differently

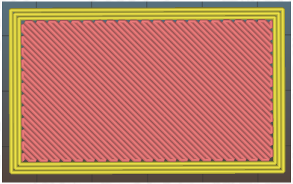


Slicing

Generating surface fill

- Each surface is filled regarding their type
- Top, bottom, internal solid usually solid
- Infill usually with infill pattern
  - Star
  - Honeycomb
  - Rectilinear
  - ...



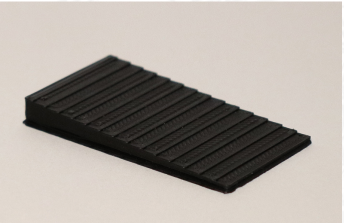


GCode Generation

Gcode generation

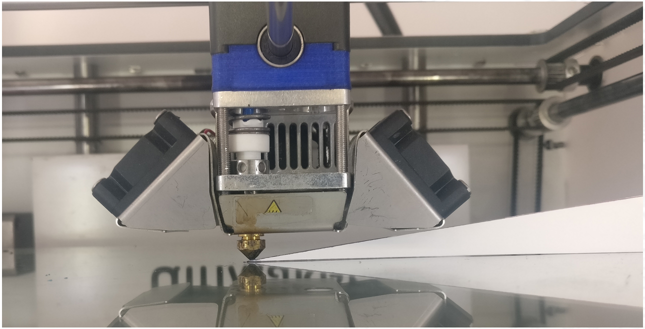
- Paths are translated to gcode Instructions
- Usually X and Y moves inside each layer
- Z moves between layers
- Extruder movement is calculated by desired line thickness and its length

```
G1 Z0.300 F10800.000
G1 E2.00000 F1500.00000
G1 F2160
G1 X112.471 Y112.315 E2.02054
G1 X112.471 Y111.261 E2.11854
G1 X111.261 Y112.471 E2.27766
G1 X110.207 Y112.471 E2.37566
```



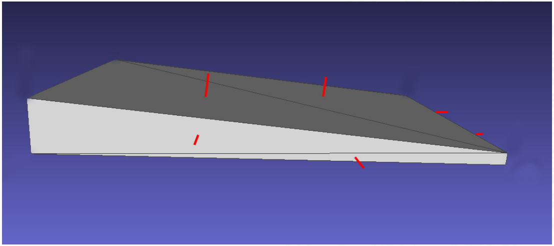
Hardware Limitations

- To prevent collisions Z movements have to be restricted
- Main limitation is the maximum printing angle
- Collision free in all directions
- Ultimaker has 8°
- Second limitation is maximum height of non planar slopes
- Pointy nozzle necessary



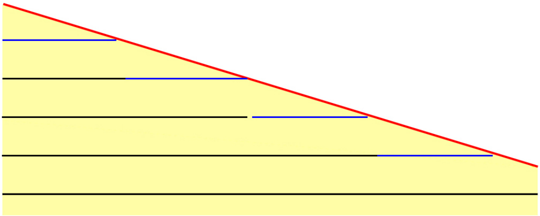
Identifying non-planar printable mesh

- Find surfaces which not exceed hardware limits
- Angle can be easily calculated by the normal
- $normal.Z >= cos(maxangle)$
- Grouped into connected components
- Check min and max of group and compare with maximum height



Identifying non-planar surfaces

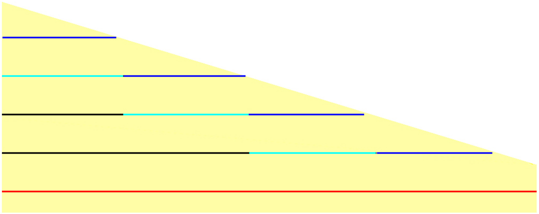
- Find top surfaces which lay below the non-planar mesh
- Mark these surfaces as top-non-planar



Slicing

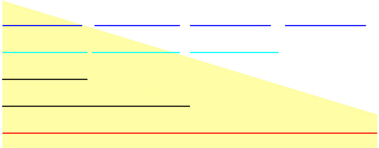
Identify shell surface areas

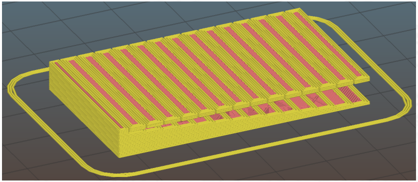
- Iterate over all layers beginning form top and identify surfaces below top-non-planar surfaces
- Mark these areas as internal-non-planar
- Remind the distance to the top layer for every surface



Move non-planar surfaces up

- Move all top-non-planar surfaces to the highest layer with non-planar surfaces
- Move the internal-non-planar layers up with the previously remembered distance

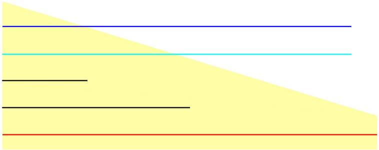


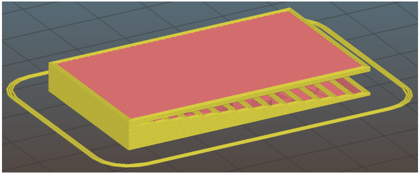


Slicing

Merge non-planar surfaces

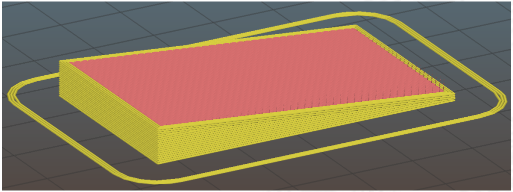
- Merge all surfaces on one layer into a single surface
- Generate perimeter and fill with planar path generation





Projection of generated path

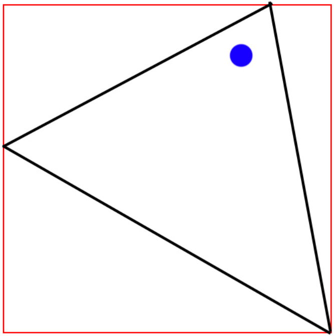
- Translate the non-planar triangle mesh to the object coordinate system
- Project each point of the path down onto the triangle mesh
- Split path up on intersections with triangle edges
- Non-planar toolpath is finished



Slicing

Point in triangle bounding box

- Check for every triangle if point is in bounding box
- To reduce more expensive point in triangle tests
- Also checks for triangles with zero surface area
- Simply check if point coordinates are between the min and max values of the triangle
- When positive, continue with point in triangle test



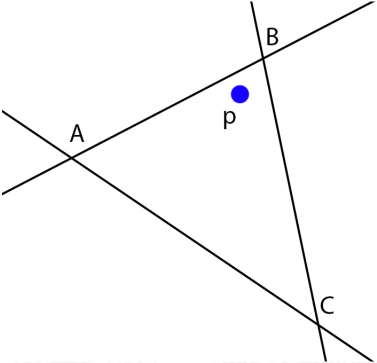
Slicing

Check if point is inside triangle

- Use same side test
- Check for every edge:

$$(B - A) \times (p - A)$$

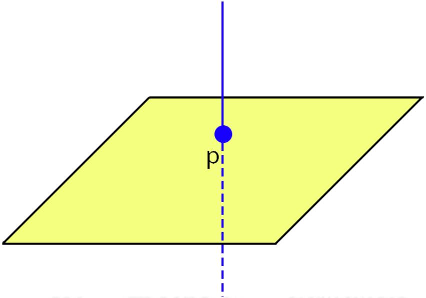
- if greater than 0 -> left of edge
- if smaller than 0 -> right of edge
- When the point is on the right of every triangle edge it lays inside the triangle



Slicing

Find line plane intersection

- Find intersection of vertical line and plane formed by the triangle
- Z of the intersection is the new Z component of the given point
- If the point is part of internal layers, it is shifted by its distance to top



GCode Generation

- Add Z component to every extrusion move
- Add Z component to every travel move
  - Move Z first on up moves
  - Move Z last on down moves
  - Always lift Z when below current layer height

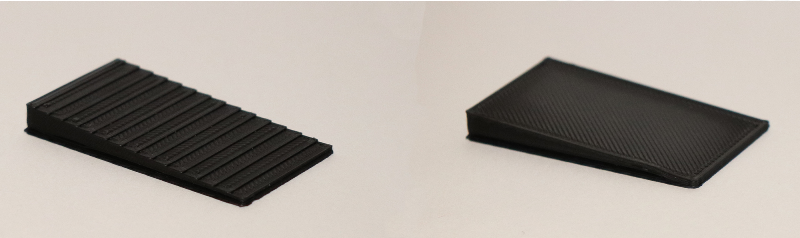
```
G1 X67.474 Y112.618 E2.00711
G1 X68.091 Y112.618 E2.04060
G1 X67.382 Y111.909 E2.09507
G1 X67.382 Y111.293 E2.12855
G1 X68.210 Y112.122 E2.19222
G1 X68.210 Y111.505 E2.22571
G1 X67.382 Y110.677 E2.28937
```

```
G1 X66.511 Y86.603 Z5.607 E2.00002
G1 X66.603 Y86.511 Z5.599 E2.00719
G1 X67.223 Y86.511 Z5.545 E2.04121
G1 X66.511 Y87.223 Z5.607 E2.09641
G1 X66.511 Y87.843 Z5.607 E2.13031
G1 X67.843 Y86.511 Z5.491 E2.23353
G1 X68.463 Y86.511 Z5.436 E2.26755
```

Printing Video

Conclusion

- Stairstepping removed on surfaces with a small slope
- Surfaces appear much smoother
- Shape error of the printed object is reduced
- Overall strength of the object is increased
- Print time is similar to the original object



Limitations

- Projection of planar path to curved surface will lead to over- and under-extrusion
- Some features of slicing unusable with nonplanar layers (adaptive layers, infill combination ...)
- Handles only top facing surfaces
- Only usable where nonplanar surfaces are printable without collision
- Printer needs pointy nozzle and some clearance to print objects

Next Steps

- Add path projection curved surfaces
- Add identification top surfaces below triangle mesh
- Add support of rotated and scaled objects
- Add collision prevention
- Add configuration option for max printing angle and clearance

Bibliography

[1] M. Micali and D. Dornfeld, “Fully Three-dimensional Toolpath Generation for Point-based Additive Manufacturing Ssystems,” in *Solid Freeform Fabrication Symposium*, 2016.

[2] A. Grutle, “5-axis 3D Printer,” Master’s thesis, University of Oslo, 2015.

[3] M. Walter, “3D printing: Non-Planar Layer FDM.” `https://hackaday.com/2016/07/27/3d-printering-non-planar-layer-fdm/`, 2016. accessed on 08 Jan. 2018.

[4] J. B. Khurana, S. Dinda, and T. W. Simpson, “Active - z printing: A new approach to increasing 3d printed part strength,” *Solid Freeform Fabrication Symposium*, 2017.

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[5] D. Ding, Z. Pan, D. Cuiuri, H. Li, N. Larkin, and S. Duin, "Multi-direction Slicing of STL Models for Robotic Wire-feed Additive Manufacturing," in *Solid Freeform Fabrication Symposium*, 08 2015.