

Considerations on 3D printing joints parts

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Abstract.: One of the unique capabilities of additive manufacturing over classical manufacturing methods is the possibility to create interlocking parts without the need of assembly. This is useful for the creation of rotational and translational joints in demonstrative or functional 3D models. This paper focuses on analyzing the process parameters which need to be considered when fabricating parts with cylindrical or spherical rotating joints using material extrusion 3D printing. Several aspects are analyzed, such as joint tolerance and clearance, surface finish requirements, surface shape and dimensions or surface precision and trueness as they result from the converting ideal CAD files to the common file formats used in additive manufacturing. The paper also searches to identify the extent to which it is possible to dynamically change process parameters such as layer height and width or depositing speed in order to improve the characteristics of the inner and outer surfaces of the joints, without influencing other areas of the fabricated parts.

1. Introduction

3D printing is implemented in a large number of industries, having an important role in reducing the time it takes for engineers and designers to go from a concept to a final product. The ease with which new models can be manufactured through additive techniques allows industry specialists to work directly with customers and integrate their feedback in the design stage. Lower-fidelity 3D printing techniques such as Fused Filament Fabrication (FFF) have allowed 3D printers to make their way into the consumer market, with users acquiring them in order to manufacture objects such as figurines, visual representations of concepts (mathematical, chemical, physics, architectural, anatomical), or enhancements for household items. According to a 2016 report by Deloitte Poland, desktop 3D printers represented 95% of the total number of additive manufacturing machines sold in 2015, with FFF being the dominant technology.

FFF is a cheaper and more consumer-friendly manufacturing process than Selective Laser Sintering (SLS) or Binder Jetting (3DP) technologies, due to the simplicity of the mechanical structure of FFF machines, as well as the lower requirements in post-processing than powder and resin techniques. The ability to fabricate larger models is also of interest for consumers.

The simplicity of FFF machines and process comes with a significant downside in terms of part layer resolution. While powder and resin-based systems can achieve resolution as high as 10 µm, enabling the manufacturing of smooth and precise functional surfaces, consumer FFF machines commonly use layer heights of 100 µm or higher. This has a significant impact on surface quality and accuracy, an important aspect when attempting to fabricate moving parts. For this reason, the majority



of research papers in this field have focused on design for additive manufacturing (DFAM) of non-assembly mechanisms for technologies such as SLA [1], SLS [2] or SLM [3]. Studies approach issues such as joint clearance [4], propose new geometries [5] or tackle the need for design feature databases [6] and design methodologies [7].

This paper looks into the possibilities offered by the FFF process to manufacture revolute joints embedded into 3D printed objects and aims to improve certain aspects of this process.

2. Joint orientation

Given the orthotropic character of parts manufactured using FFF, the orientation of joint axis during the fabrication process is very important, as it is one of the main factors that determine part surface accuracy and part strength [8].

Horizontal orientation of the journal axis provides the highest part strength, as loads will be distributed perpendicular to the length of the deposited filament [9]. There are several methods of fabricating rotational joints in a horizontal orientation. One method requires the journal to be fixed at both sides, using FFF-specific bridging capabilities for the suspended part of the joint. This is the simplest method to model for and to fabricate. Several factors are to be considered during such a fabrication method, such as printing speed and adequate cooling of the bridged area. Another method relies on fabricating an unsupported journal by using a small gap between surfaces of the journal and the bearing. The gap and the circular section of the deposited filament will create a weak fusion between components. Rotating the joint requires breaking of the small volume of fused material between the two joint components.

Achieving precise 3D printed circular sections in a vertical plane is very difficult, due to the layering aspect of FFF. Circular sections, when fabricated in a vertical plane, require very steep overhang angles starting at the base of the journal as well as at the top of the bearing (Figure 1). Furthermore, common Cartesian 3D printers are capable of different positioning accuracy in the horizontal plane, determined by the kinematic chain of X and Y axis, which are usually belt driven, than in the vertical plane, determined by the Z-axis, commonly driven by a trapezoidal drive screw and nut mechanism. Figure 2 shows the difference between surface finish for cylindrical surfaces, depending on the position of the surface in question relative to horizontal and vertical axis.

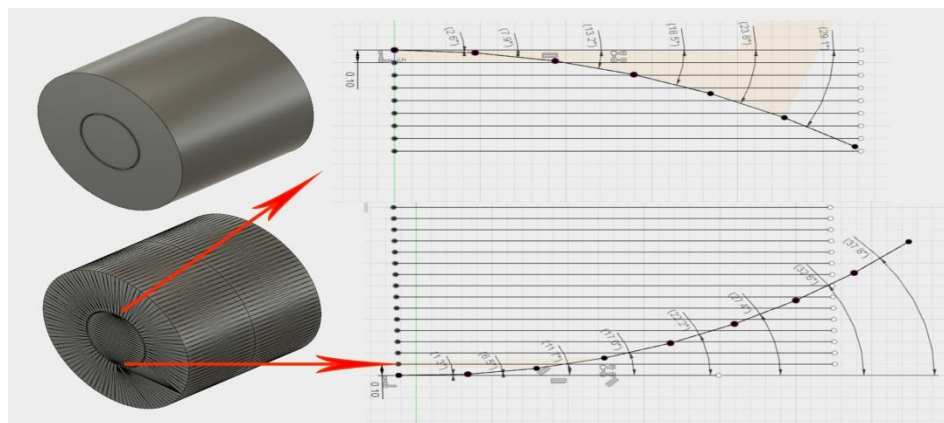


Figure 1. Overhang angles for revolute joints in horizontal axis orientation.

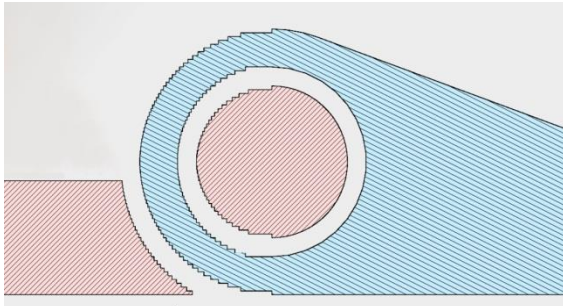


Figure 2. Cylindrical surface quality - differences generated by the layered aspect of FFF.

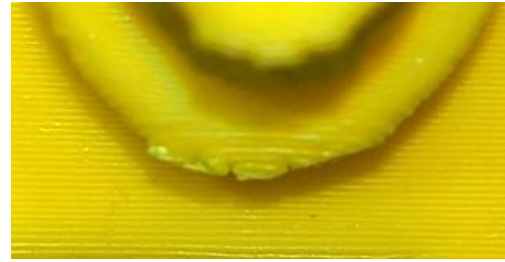


Figure 3. Defect caused by steep overhangs in revolute joint journal.

A vertical orientation of the revolute joint axis provides less strength than the horizontal orientation, due to loads being applied in the same plane as the printed layer, resulting in joint weakness to shear forces. However, to fabricate the circular section of the joint in a horizontal plane, the machine moves the two horizontal axis, X and Y, which commonly have identical drive mechanisms.

With vertical orientation of the joint, the issue of axis perpendicularity plays a bigger role in determining the end results. A machine that does not have perfectly perpendicular X and Y axis will be unable to provide the required precision to produce a working joint (Figure 4.a), while calibration of X and Y axis will produce functional revolute joints (Figure 4.b).

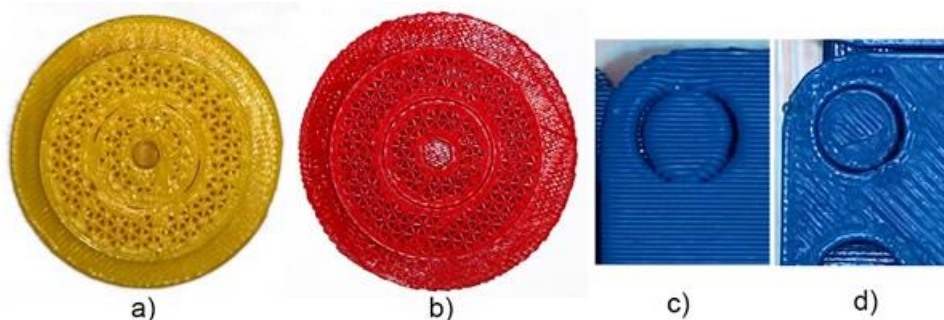


Figure 4. Joint clearance a) Uncalibrated X, Y axis b) calibrated X, Y axis; c) Revolute joint with horizontal axis; d) Revolute joint with vertical axis.

3. Z-axis layer transition seams and area start and ending points

Using FFF, a part is built by stacking horizontal layers of materials one on top of the other. At the transition between these layers, the build platform needs to move in the Z-axis while the extrusion nozzle stays still in the XY plane. This results in a small defect in the part, as extruded material accumulates at the tip of the extruder nozzle during the layer increments. Common slicing software programs use several methods of dealing with the z-axis layer seams. The first method is finishing the horizontal layer and starting the Z-axis layer transition in random locations for each layer, which distributes the Z-axis transition defects in random locations, eliminating the visual effect of a seam. However, these defects still exist and can impair the function of a rotational joint. Another method is placing the Z-axis transition in a spot which is easily accessible for the seam to be removed in post processing. In the case of rotation joints, this variant is not always applicable.

A similar defect in surface quality forms at the entry and exit points of the extruder during the transition between isolated section areas of the fabricated part.

We propose a method of dealing with Z-axis seams in rotation joints, by "hiding" the layer change seam and the area entry and exit points in radial grooves in the inner or outer part of the joint, where they do not influence the functional surface (Figure 5). Radial grooves can be parametrically modeled into the 3D CAD models of the parts by defining the joint inner and outer surfaces. Measurements on parts fabricated on desktop FFF printers show that the seam defect can extend up to 0.3 mm from the surface, indicating that the groove method can be used even with small articulated joints.

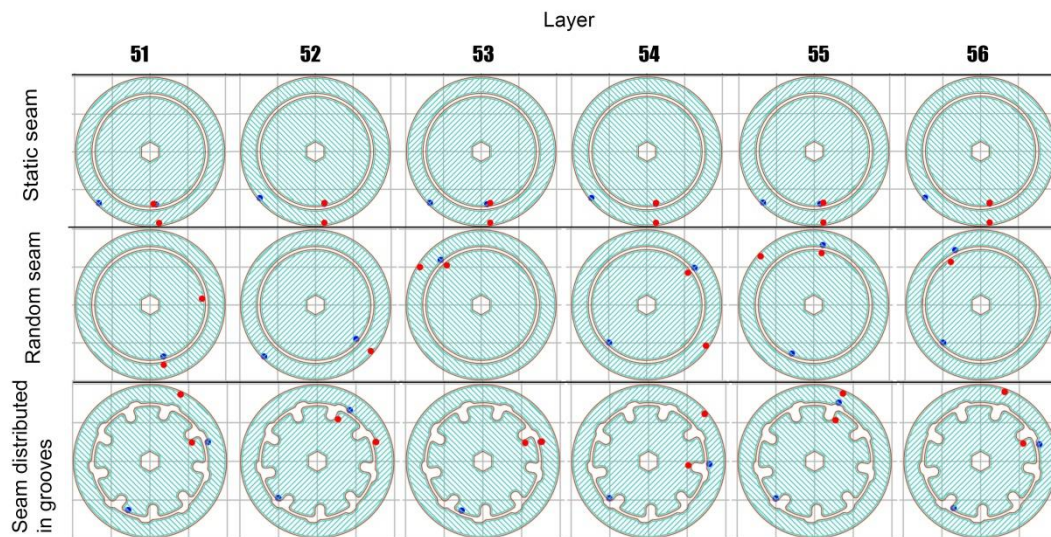


Figure 5. Distribution of layer change points in a revolute joint. Top row - Static seam; Middle row - random seam; Bottom row – Seam distributed in grooves.

While having 1 groove is sufficient to eliminate the influence of the defect by moving it away from functional surface, multiple grooves can be used in order to simplify the extruder printing trajectory and shorten print time.

Grooves can be modeled into the inner surface of the joint, as well as into the outer surface. Because of 3D printing machines dynamics, it is recommended that the groove has no sharp angles, as the quick direction changes needed to follow such a path can introduce vibrations that produce defects commonly known as "ghosting" or "ringing". It is important to note when calculating the joint clearance required for a revolute joint that different materials will experience different amounts of shrinkage during the printing process.

4. Impact of STL conversion

For FFF, the main file format used by common slicing programs is the STL format. During the conversion to STL format, all surfaces of 3D models are divided into flat triangular surfaces. For initially curved surfaces, this conversion comes with a loss of surface accuracy [10], impacting the precision of fabricating 3D-printed joints.

In order to analyze the influence of file conversions on assembly clearance while using one of the more common ways to create files for use in a desktop 3D-printer, a multi-parameter analysis was performed. The parameters taken into consideration for this analysis are joint inner radius, modeled gap and mesh refinement.

3D models simulating cylindrical, tapered cylindrical and spherical joints have been designed in Autodesk Fusion 360 (Figure 6). These models have then been converted into STL file formats using the program's embedded conversion tool. In order to perform an interference analysis which can determine the minimum distance between the inner and outer parts of the joints, the resulted STL file

has been reconverted into a boundary representation file (BRep). The conversion tool embedded in Fusion 360 has 3 different settings concerning mesh refinement: low, medium and high. When varying the joint gap parameter, the inner joint part was kept the same, while the dimensions of the outer joint part were changed to accommodate the new gap value.

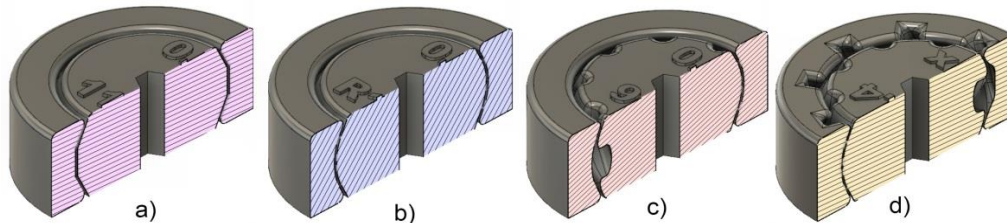


Figure 6. Test revolute joints: a) Cylindrical, tapered joint; b) Spherical joint; c) Spherical joint with grooved journal; d) Spherical joint with grooved journal and bearing.

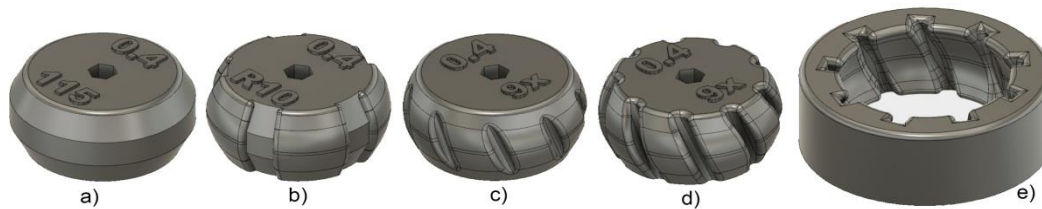


Figure 7. Groove designs: a) Non-grooved journal; b) Straight journal grooves; c) Angled journal grooves; d) Deep angled journal grooves; e) Bearing grooves.

The results show that surface precision losses due to file conversion are significant when using the lower-end mesh refinement. As this option is used increasingly with large assemblies in order to reduce file size and processing time, it is recommended to manually increase mesh detail in joint surfaces, or use a dynamic meshing process. As it can be observed in Figure 8, STL conversion produces a bigger error for spherical joints, compared to tapered cylindrical, or simple cylindrical joints.

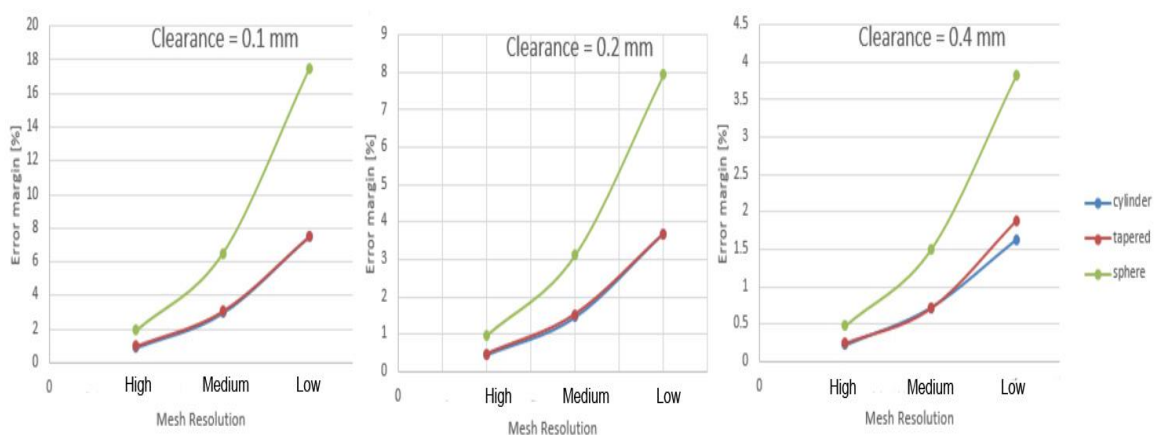


Figure 8. Error margin of joint clearance depending on mesh refinement and joint surface type.

5. Dynamic parameter variation

As shown previously, surface finish and accuracy are key elements when attempting to fabricate revolute joints. In FFF processes this means utilizing lower layer heights and printing speeds, which

increases the fabrication time. An attempt of printing time while maintaining the functional characteristics of the part has been made.

By utilizing tools embedded in slicing software such as Cura 3.0.3, it is possible to define different parameters for outer surfaces than for part infill. Figure 9 presents 2 parts manufactured using 0.15 mm layer height and 70% infill [Figure 9.a]. The second part [Figure 9.b,c] uses the same 0.15 mm layer height for its outer surfaces, and a 0.30 mm layer height for infill. In this case, the printing time has been reduced from 1 hour 57 minutes to 1 hour 40 minutes. While this 15% reduction in print time is significant, fabrication time can still be lowered through optimization.

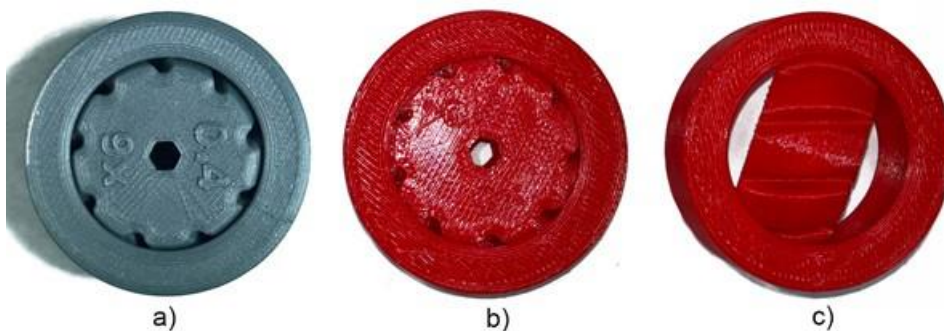


Figure 9. Reduction of print time based on variation of infill : a) part printed with infill layer height equal to perimeter height; b), c) part printed with higher infill layer height.

Figure 10 presents a simple horizontal hinge, for which we aim to lower the fabrication time, while maintaining the part functionality. An initial sectioning of the part was done with settings that provide an acceptable result in terms of form & function. The initial print time was calculated to be 1 hour 53 minutes (Figure 11.a). In the print time optimization process, the mesh around the joint has been split and then reattached to the model in order to define a volume which will use different process parameters than the rest of the part. The infill in the joint region has been increased to 100% in order to provide strength to the journal (Figure 11.b). Layer height was maintained at 100 μ m around the joint but was increased to 200 μ m for the rest of the hinge. Printing parameters used to fabricate these test parts are shown in table 1.

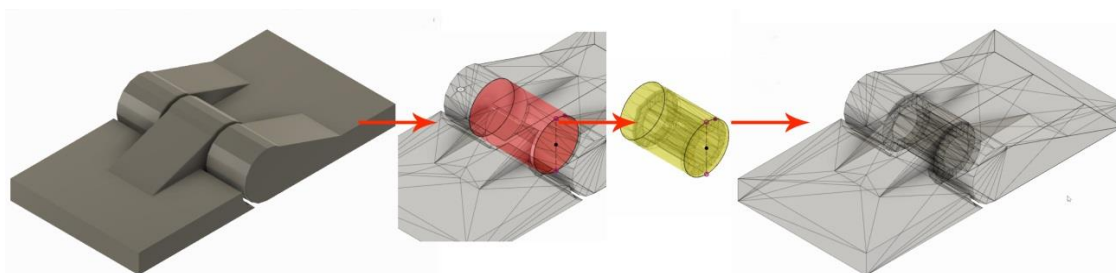


Figure 10. Selection of joint area used for optimization.

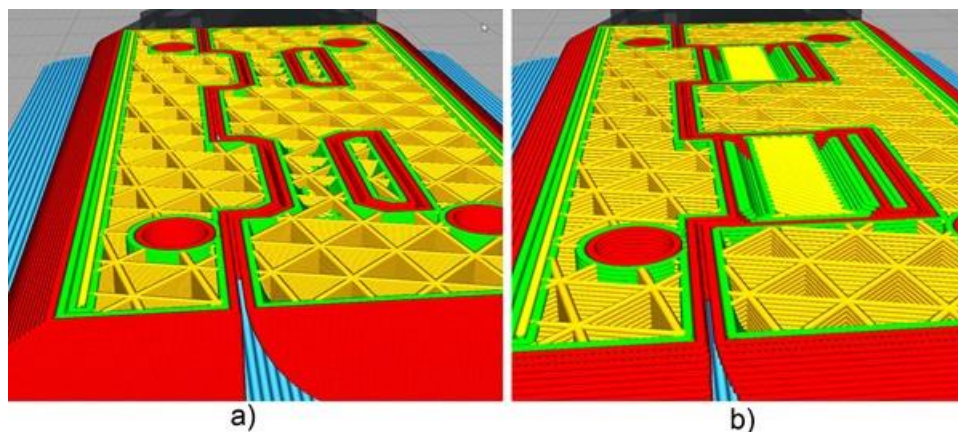


Figure 11. Slicing of a revolute joint in a simple hinge; a) standard sectioning b) optimized slicing .

Table 1. Print parameters.

Parameter	Part A	Part B	Part B Joint
LayerHeight	100 μm	200 μm	100 μm
Infill	40%	40%	100%
Perimeter width	0.8 mm	0.8 mm	0.8 mm
Print Speed	50 mm/s	50 mm/s	40 mm/s
Print Time	113 min	78 min	

6. Conclusions and future work

Choosing a specific orientation for a joint axis comes with both advantages and disadvantages, the optimal solution being a trade-off between joint strength and precision. For revolute joints, surface quality is important and the elimination of defects caused by extruder transitions from functional surfaces is necessary. To tackle this issue, several grooved joint models were designed and fabricated. Deliberately positioning defects common to FFF on surfaces which do not serve a functional role allowed the improvement of joint clearance.

When designing joint surfaces and dimensions, an analysis was made regarding 3D model conversion into the STL format used by most desktop 3D printers. To achieve tighter clearances, it is recommended that a non-homogenous meshing algorithm is applied, with better mesh refinement around the area of the joint.

Print time and joint parameters were optimized for a simple hinge using a manual approach, with results offering the same functional surface quality with a 40% reduction in print time for the tested model, while improving joint strength. Future work will aim to automate this process by automatically recognizing joint surfaces defined in CAD software and defining the volumes which will be printed using different sets of parameters. Similarly, grooves can be automatically modeled into the joint surfaces.

Acknowledgements

This work has been funded by University Politehnica of Bucharest, through the “Excellence Research Grants” Program, UPB – GEX 2017. Identifier: UPB–GEX–2017, 3D printing integrated system of joint parts, contract number IM 21-17-05/2017.

7. References

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