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55th CIRP Conference on Manufacturing Systems

Orientation smoothing in multi-axis additive manufacturing

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Abstract

In multi-axis processes, such as material extrusion like Fused Filament Fabrication (FFF), the orientation of the tool relatively to the workpiece is usually set by the CAM software to an angle that is locally constant relative to the manufacturing surface. However, in the case of large curvature gradients or small curvature radius of the surface or the path, this method leads to significant variations of the tool orientation. These variations require large compensating movements of the axes to maintain the desired deposition tool orientation along the path. Kinematic constraints such as acceleration or jerk limits can lead to a reduction of the path velocity or noticeable positioning errors along the movement, as well as unwanted vibrations, which means poor process conditions and defects in the parts. The paper presents a post path planning algorithm that allows smoothing of the tool orientation to avoid jerky compensation motion of the CNC system by varying the orientation within a defined tolerance. This tolerance depends on the deposition process, and is determined experimentally for a FFF process. The proposed methodology was successfully validated by the manufacturing of two sample parts using a robotic additive manufacturing cell.

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Keywords: Additive Manufacturing; Robot; Machine tool; Optimization; Tool path

1. Introduction

Multi-axis Additive Manufacturing (AM) systems are more and more widely used in the industry considering their main advantages, namely huge building volumes and high productivity. Robot-based direct deposition systems also allow reduced investment costs. Thanks to these systems, it is possible to manufacture complex shapes without using support material, either with polymer materials through FFF (Fused Filament Fabrication) or metals through DED processes (Directed Energy Deposition). However, the optimal use of such systems requires to control the whole CAD-CAM chain, including non-planar path generation and multi-axis control.

Among all possibilities, a critical task is to manage path tangency discontinuities, which are responsible for jerky variations

of orientation (Figure 3). In such situations, the robot's motion can be severely affected and cause local deposition defects such as over deposition due to the change of travel speed, collisions due to a badly controlled position, or vibrations caused by high accelerations.

This paper describes a smoothing algorithm that is focused on the tool/part relative orientation smoothing in order to solve the problems mentioned above. A state-of-the-art of the theoretical background related to multi-axis AM and discontinuities management is presented in the next section. Then the concepts of the proposed orientation smoothing methodology are introduced in Section 3. Experimental apparatus and results are reported in Sections 4 and 5 to validate the method. The case studies are complex tubular parts manufactured using a robotic 6-axis FFF system; but the possible applications are wider, including DED processes (such as WAAM and LMD) or even ball milling.

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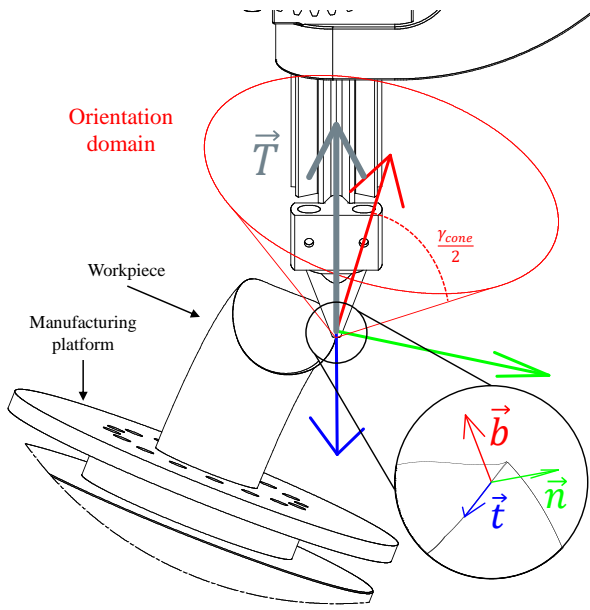


Figure 1: Definition of the local basis and the orientation domain about \vec{b} .

2. State of the art

AM trajectories can be decomposed into a manufacturing path, *i.e.* the curves followed by the deposition tool, and a tool vector that describes the orientation of the tool/the part or both in the manufacturing space. For a defined part geometry and a fixed path strategy, the only way to optimize the manufacturing device motions is the tool vector orientation [1]. Thus, this state of the art presents generation methods for the tool orientation, manufacturing management of path discontinuity areas and tool orientation smoothing algorithms.

2.1. Orientation domain for FFF/DED manufacturing

The generation of multi-axis AM trajectories needs the definition of a build-direction vector, denoted \vec{b} , in order to orient the part and/or the deposition tool in a way that the part being manufactured always lies under the deposition point [2]. Concerning non-planar manufacturing paths, this vector must be defined at each point of the path [3]. For the manufacturing of thin-walled parts, the local build-direction vectors can be defined as normal to the manufacturing path and tangent to the surface, therefore being orthogonal to \vec{t} and \vec{n} respectively the tangent vector to the path and the normal vector to the surface, in order to have a local orthonormal basis $(\vec{t}, \vec{n}, \vec{b})$ [4], Figure 1.

When using FFF or DED processes, the deposition is possible even if the axis of the deposition tool, \vec{T} , is not collinear with the build-direction vector \vec{b} [1, 5], as represented in Figure 1. Therefore, it is possible to define an orientation domain of the deposition tool (shown in Figure 1) about the \vec{b} vector, allowing an acceptable deposit in terms of quality and geometry [5]. Within the orientation domain, which has to be identified for each process and material, the tool vector can be

defined with two tilting angles, one in the feeding plane and the other in the normal plane [4]. Thus, this orientation domain is defined as a pyramid, and can be simplified by a cone with an angle γ_{cone} [6], as represented in Figure 1.

2.2. Manufacturing management in discontinuity areas

Tangent discontinuities in manufacturing trajectories are undesirable because they can lead to a degradation of the quality of the manufactured part. In addition to a null travel speed, causing an over-deposit at the discontinuity point [7], discontinuities imply huge and sudden variations of the orientation of the build-direction vector, and consecutively jerky motions of the different axes of the manufacturing device [6].

To minimize the effect of the trajectory discontinuities on the manufactured part quality, one method consists in modifying the deposition parameters according to the real travel speed [7] or based on deposition simulations [8] in order to avoid over-deposition. However, fast and sudden movements of the different axes of the manufacturing device can still happen.

Another method to manage the manufacturing in the tangent discontinuity areas consists in the modification of the path to avoid the discontinuity point, especially in the case of T-cross or X-cross [9]. Boisselier *et al.* [10] showed the effects of smoothed paths on the part properties in the case of 5-axis process. However, these methods may not be suitable for all kind of parts, especially for thin-walled ones.

A last method to manage the manufacturing in tangency discontinuity areas consists in a smoothing of the tool orientation. This smoothing can be done online by the control device, as proposed in the Siemens 840D sl CNC controller [11], or offline by a path-planning post-processor, globally or locally near the discontinuity. It can also be used to optimize the machine motion or to avoid collisions [12].

If online smoothing is dedicated to a specific machine and is subject to real-time conditions, offline methods can be more complex and implemented without regard to the configuration of the machine. Thus, for local corner smoothing for machining, either Bézier curves [13], B-Splines [14] or pythagorean hodograph curves [15] are found in the literature to be used at critical sections of the manufacturing path, in combination with parameters used to control the maximal deviation. Similarly, global smoothing can be done by fitting spherical splines to the originally computed orientation vectors [16]. Alternatively, if the orientation is defined by two points along the tool as proposed by Langeron *et al.* [17], standard splines can be fit to the second point along the tool [18].

In the FFF field, Dai *et al.* [19] proposed the distinction between orientation continuity and pose continuity. Then, a low-pass filter is used to achieve orientation continuity and, for crest regions, an intermediate computation of the orientations by quaternion interpolation based on a subdivided path. For AM applications, Zhang *et al.* [20] proposed also a Laplacian-based smoothing taking into account the problem of singularities in robot configurations. It is also possible to use tool tilting in order to anticipate strong changes in the build-direction vector orientation and then improve the movement quality while

keeping a travel speed as constant as possible [6]. This problem has also been studied for machining applications as proposed by Jun et al. [21] for surface milling with configuration-space methods determining valid tilt angles at each path point, and then solving an optimization problem that selects an orientation for each point to minimize the variation of orientation angles. An optimal control problem used to achieve a time-optimal solution for manufacturing path planning using tool tilting is also described by Wulle et al. [6]. In this case, tilting is allowed within an angular domain that can be defined as a pyramid in order to respect the maximal tilting angles allowed in both directions or simplified by a cone, as represented in Figure 1.

3. Concept of orientation smoothing

3.1. Evaluated CAD-CAM-chain

The generation of the manufacturing path is achieved from a parameterized surface of a tube to have a constant local distance between layers [22]. The CAD-CAM chain is home-made and includes four main steps : non-planar path planning at constant inter-layer distance, local build-directions generation, orientation smoothing and program writing. The first two steps generate the manufacturing trajectory, as displayed in Figure 2, then the build-direction vectors are smoothed if needed, and finally, the trajectory is post-processed so that the machine controller can read the manufacturing program.

However, in the case of over-hanging thin-walled tubes, the trajectory generation produces tangent discontinuities in the path. As the local build-direction vectors are generated tangent to the surface and normal to the path, as described in Section 2.1, these discontinuities involve considerable changes in the tool orientation. In this work, two study-cases have been considered: a quarter of torus and a square shaped tube. The equations used for the guide curve $(X_{g_t}, Y_{g_t}, Z_{g_t})$, parameterized by t , and the variation of the radius of the tube $(\rho_{t,v})$, where v is a polar parameter, are respectively detailed in Equation 1 and Equation 2 for the two case studies. The generated trajectories are displayed in Figures 2a and 2b.

Once the trajectories have been generated, the available data are the coordinates of the manufacturing path and the coordinates of the local build-direction vectors.

$$\begin{aligned} X_{g_t} &= R \cdot \cos t - R \\ Y_{g_t} &= 0 \\ Z_{g_t} &= R \cdot \sin t \\ R &= 50 \text{ mm} \\ \rho_{t,v} &= 15 \text{ mm} \end{aligned} \tag{1}$$

$$\begin{aligned} X_{g_t} &= Y_{g_t} = 0 \\ Z_{g_t} &= t \\ \rho_{t,v} &= \frac{15 \cdot \left(1 + \frac{t^2}{400}\right)}{\sqrt{1 + \sin 2 \cdot v} + \sqrt{1 - \sin 2 \cdot v}} \end{aligned} \tag{2}$$

3.2. Hybrid orientation smoothing approach

The novel hybrid smoothing approach aims at smoothing the orientation in the trajectory while keeping a certain tolerance range. Based on these requirements, a methodology consisting of a primary vector smoothing and a secondary orientation tolerance range correction was developed. Therefore, the sequence of the approach is:

1. Smoothing of the tool orientation $(\overrightarrow{T_{S,m}})$:
 - With median filter (+zero phase filter)
 - With moving average filter (+zero phase filter)
2. Correction of the smoothed orientation within the tolerance range.

In the following, the individual steps and variants of the procedure are explained. The smoothing process should cause as little change in orientation as possible in order to reduce the high jerk values in the process and thus also in the machine drives. Here, only the orientation is considered and not the manufacturing path. For such smoothing problems, established methods such as median filter or moving average filter are suitable. The median filter operates in a moving window over a signal and calculates the median value of the data set. For a set point m , the smoothed median vector $\overrightarrow{T_{S-MED,m}}$ of $W = \{\overrightarrow{b_m} : m = 1 \dots n\}$ is calculated by sorting the entries by size and selecting the mean value.

A well-known possibility for smoothing, especially in the field of real-time data processing, is the moving average filter. The smoothed moving average filter vector $\overrightarrow{T_{S-MA,m}}$ is defined as follows in a window of n values:

$$\overrightarrow{T_{S-MA,m}} = \frac{\overrightarrow{b_m} + \overrightarrow{b_{m-1}} + \dots + \overrightarrow{b_{m-(n-1)}}}{n} = \frac{1}{n} \sum_{i=0}^{n-1} \overrightarrow{b_{m-i}} \tag{3}$$

Since the above filter methods are defined with a delay, with a backward running window, the output of the smoothing is phase-shifted. This would lead to a lagging of the orientation in the process. A remedy is to apply zero-phase filters. A zero-phase filter consists of a forward and backward filtering in such a way that the phase of the filtering remains zero [23]. This filter type is implemented in Matlab® as *filtfilt*.

After smoothing the orientation, it must be verified whether the solution of $\overrightarrow{T_{S,m}}$ lies within the permissible tolerance range. The tolerance range is assumed to be a cone about $\overrightarrow{b_m}$ with an opening angle γ_{cone} (Figure 1). Therefore, the angle α_m between $\overrightarrow{T_{S,m}}$ and $\overrightarrow{b_m}$ for each set point m is calculated as:

$$\alpha_m = \arccos \left(\frac{\overrightarrow{T_{S,m}} \cdot \overrightarrow{b_m}}{\|\overrightarrow{T_{S,m}}\| \cdot \|\overrightarrow{b_m}\|} \right) \tag{4}$$

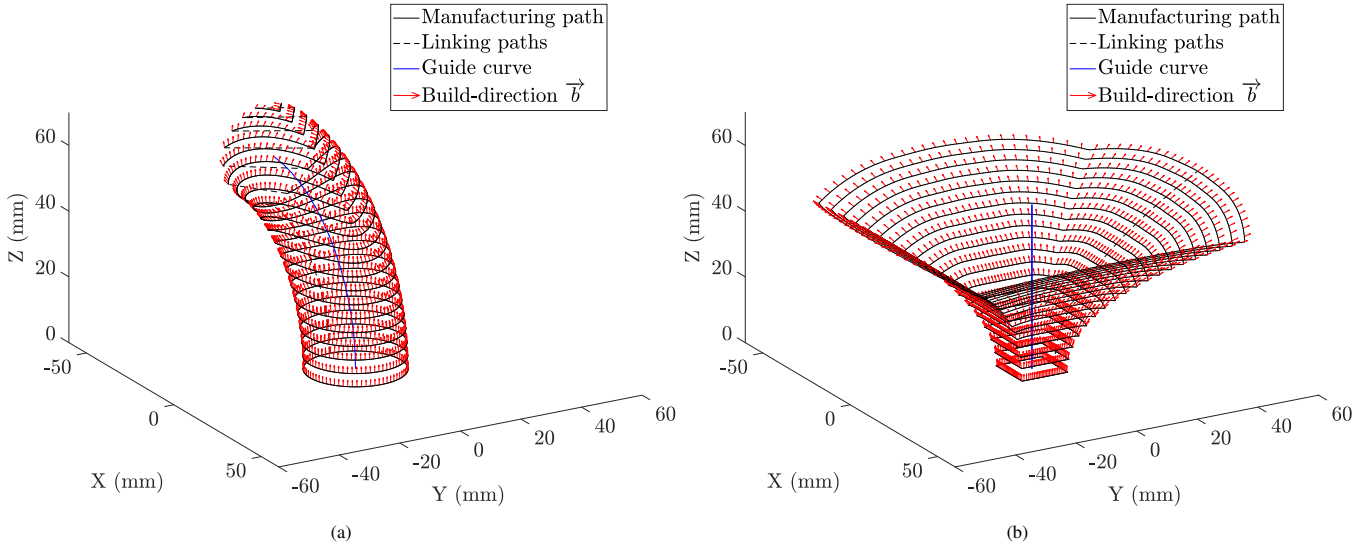


Figure 2: Manufacturing trajectories presenting tangent path discontinuities. a: Quarter of torus ; b: Square shaped tube.

Based on this variation between the smoothed and the unsmoothed vectors, it can be compared whether it is still within the tolerance cone range $\gamma_{cone}/2$. If the smoothed vector is out of the tolerance cone, it will be shifted back to the periphery of the cone. In this case, the vector is rotated from \vec{b}_m about an auxiliary normal axis \vec{h}_m , defined in Equation 5, with the rotational matrix $\underline{\mathbf{R}}_m$ defined in Equation 6. The tool vector is then defined as described in Equation 7. Figure 3 shows the tool orientation smoothing for one layer using different approaches, by using a moving average filter and a zero-phase moving average filter.

$$\vec{h}_m = \vec{T}_{S,m} \wedge \vec{b}_m \quad (5)$$

$$\underline{\mathbf{R}}_m = \begin{bmatrix} c + h_x^2(1-c) & h_x h_y(1-c) - h_z s & h_x h_z(1-c) + h_y s \\ h_y h_x(1-c) + h_z s & c + h_y^2(1-c) & h_y h_z(1-c) - h_x s \\ h_z h_x(1-c) - h_y s & h_z h_y(1-c) + h_x s & c + h_z^2(1-c) \end{bmatrix} \quad (6)$$

with: $c = \cos(\gamma_{cone}/2)$; $s = \sin(\gamma_{cone}/2)$; $h_{x/y/z} = h_{m,x/y/z}$

$$\vec{T}_m = \begin{cases} \vec{T}_{S,m} & \text{for } \alpha_m \leq \gamma_{cone}/2 \\ \underline{\mathbf{R}}_m \times \vec{b}_m & \text{for } \alpha_m > \gamma_{cone}/2 \end{cases} \quad (7)$$

4. Device and Setup

The AM cell of the University of Toulon, displayed in Figure 4, and used to validate the smoothing algorithm, is composed of a 6-axis Fanuc ARCMate 120iC robot coupled to a home-made vertical extrusion system. This deposition system uses a PLA wire (\varnothing 3 mm) with a nozzle diameter of 1 mm and is designed to minimize collisions with the part or the robot during the manufacturing. For the deposition, the set Travel Speed

(TS) is 36 cm/min and the set Wire Feed Speed (WFS) is 10 mm/s.

The manufacturing configuration is a fixed extrusion system and a mobile building platform on which the part is manufactured. Such a configuration allows the manufacturing of cantilevered parts without supports by keeping the part being manufactured always under the deposition point while allowing tool tilting, as represented in Figure 1. However, if the speed is managed conventionally with this kind of configuration (*i.e.* the travel speed is managed at the Tool Center Point - TCP), the travel speed at the deposition point may not be the same than the one at the TCP point, especially when rotational and linear motions are needed to follow the trajectory. To avoid this issue, the Fanuc RTCP (Remote TCP) function is used to manage the speed relatively to a fixed point, corresponding to the deposition point, in the cell space.

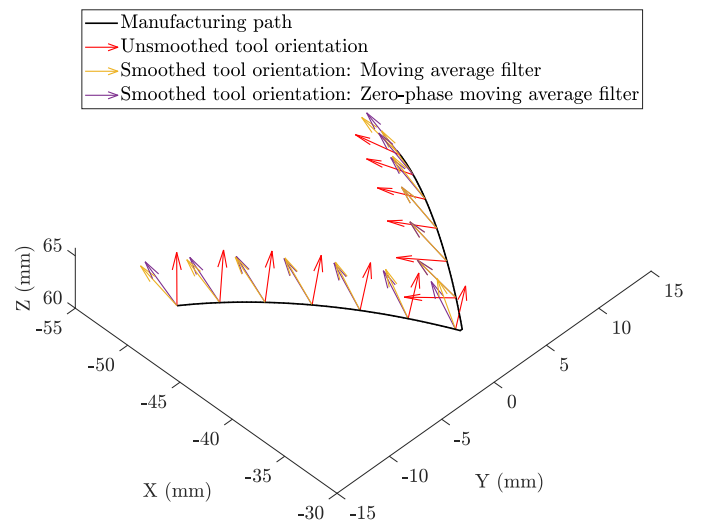


Figure 3: Tool orientation for one layer with different smoothing methods.

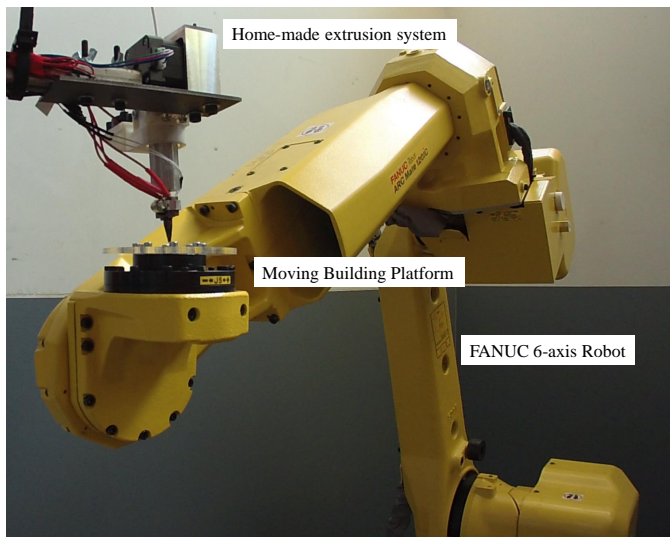


Figure 4: Robotized AM cell of the University of Toulon.

5. Experimental Results

5.1. Orientation tolerance determination

In order to determine the orientation tolerances for the FFF process using PLA with our deposition system, trial tests consisting in thinwall cylinder manufacturing using combined tilting angles in both planes were carried out. The limits of the orientation tolerance for a simultaneous combination of tilt about the \vec{i} vector and about the \vec{n} vector are -30° to 30° each. Therefore, the orientation tolerance has a pyramidal shape with a 60° opening angle. In the individual $\vec{b} - \vec{i}$ -plane, even deviations of $+50^\circ$ and -30° about the \vec{n} -axis are possible without identifying geometric or quality losses. For the rest of the study, the tolerance shape that is adopted is a cone with a 60° opening angle lying inside the pyramid, allowing the correction of the smoothed orientation using Equations 5 to 7.

5.2. Validation on sample parts

In order to validate the approach, two parts were selected in which paths present tangency discontinuities. These two parts are a quarter of torus and a square shaped tube, whose trajectories are calculated to ensure constant inter-layer distance (Figure 2).

The manufacturing path used for the fabrication of the square shaped tube presents tangency discontinuities at each corner of the geometry due to its definition. However, although there is tangency discontinuity in the path, the manufacturing trajectory does not imply huge changes in the build-direction vector orientations. This first case-study was so selected because of the small orientation changes allowing the smoothed tool vector to stay in the tolerance cone.

The different smoothing methods were investigated for this test component. Zero-phase filters generally show better results, as they do not lag behind in orientation in the TCP. The moving-average filter with 100 interpolation points corresponding to a path section of about 20 mm, has a decrease in orientation vari-



Figure 5: Manufactured square shaped tube: zero-phase moving average filtering smoothing.

ations. The median filter had too little effect in the local area. For this example, an orientation cone tolerance of 60° was defined. The part manufactured with smoothed tool orientation is shown in Figure 5.

The smoothed orientation in the manufacturing process made it possible to create a smooth transition in the corners. In contrast to the default variant, the dynamic limits of the robot were not exceeded, which is directly reflected in the process and in the manufacturing result.

For the second case study, the quarter of torus, the manufacturing path presents tangency discontinuities starting from a certain layer, which are due to the manufacturing path generation at constant inter-layer distance and not because of the part's geometry. Therefore, as the build-direction vectors are generated tangent to the surface and normal to the path, the tangency discontinuities in the manufacturing path imply huge gradient of the build-direction orientations, as shown in Figure 3.

In order to smooth the tool vector orientation, a zero-phase moving average filter was also used here. First, a tolerance cone of 60° was selected. At the discontinuity point, the tolerance cone is reached, which still leads to jerky changes of orientation. Therefore, the tolerance was increased up to 90° because the orientation difference between two build-direction vectors near some discontinuity points was so important that the corrected orientation within a tolerance range of 60° still involved strong machine movements.

The parts manufactured with and without smoothing are displayed in Figure 6. It can be observed that the part manufactured without smoothing shows poor surface quality with a heterogeneous wall thickness and a lack of material in the tangency discontinuities areas combined with a series of crushed beads due to collisions between the part being manufactured and the extrusion nozzle. These collisions are due to the strong and jerky movements of the robot that are requested to follow the programmed tool orientation in the discontinuity areas, leading to the non-respect of the manufacturing path. In contrast, the part manufactured with a smoothed orientation of the tool vector shows a better surface quality without lack of material but with over-deposit at the discontinuity point due to a null travel speed.

6. Conclusion

In this paper, a hybrid orientation smoothing approach for multi-axis AM has been presented. The approach is composed

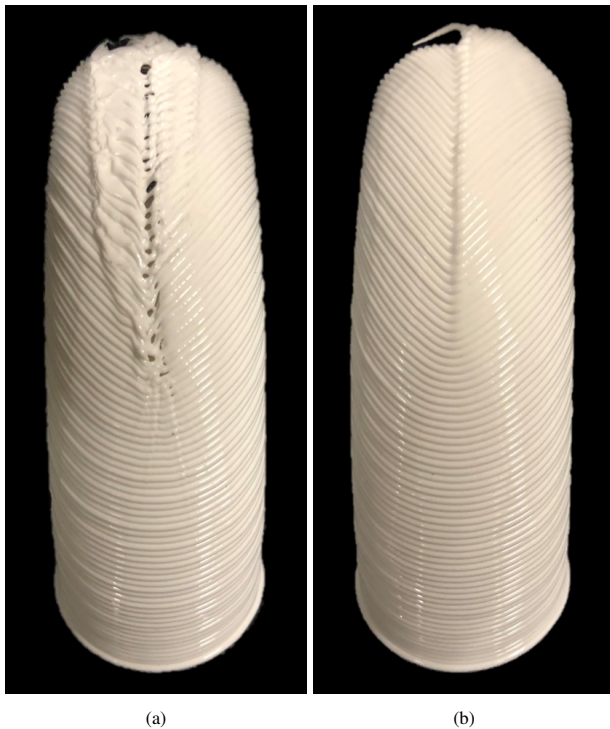


Figure 6: Manufactured quarter of torus parts. **a**: Without smoothing ; **b**: With smoothing - Zero-phase moving average filter.

of a smoothing step followed by a correction step, which is able to generate smoothed orientations within predefined orientation tolerance ranges. The proposed approach is helpful for the manufacturing of parts presenting tangency discontinuities in the path where huge tool orientation variations can occur, involving strong and sudden machine movements.

The manufacturing trials, applied to two case-studied parts and performed with and without smoothing, show the benefits of a smoothed orientation, namely constancy in the wall thickness and better surface quality as the travel speed is more uniform and the kinematic limits non reached.

Future work will deal with integrated orientation optimizations, also considering collisions.

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