Title:
Non-Uniform Planar Slicing for Robot-Based Additive Manufacturing

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Introduction:
In Additive Manufacturing (AM) products are usually built along a Z direction identified as the normal to an optimal slicing plane. Planar slicing algorithms with constant layer thickness are widely implemented in commercial software due to their simplicity, robustness, and limited processing time. However, this strategy results in staircase effect for processed surfaces that are tilted with respect to the slicing direction, decreasing the surface finish of the final product. The staircase effect can be evaluated by measuring the cusp height. This index describes the maximum deviation between printed part and model surface [2]. Planar adaptive slicing algorithm was developed to control the staircase effect [9], as depicted in Fig. 1a. This approach foresees the variation of the layer thickness according to the shape of the processed CAD, balancing the staircase effect with the manufacturing time. Adaptive strategies can be found in commercial slicing software. However, process parameters must be adapted according to the desired layer thickness, considering minimum and maximum thickness limits of the printing device.

Usually, the adoption of a fixed slicing direction with planar uniform or adaptive slicing leads to suspended or floating geometry regions where the supports are required, reducing also the contact area between two consecutive layers [3]. Supports must be removed by a physical, chemical or thermal process. This post-process phase can damage the final product, reducing the surface finish. In this context, Robot-Based Additive Manufacturing (RBAM) can overcome these limits. RBAM is the combination of additive process and manipulators and/or working table with multiple degrees of freedom [5]. For example, an extruder or a welding torch can be attached to a robot arm. These solutions are used to increase the manufacturing flexibility of cartesian AM [6], enabling the deposition of material along multiple directions. In particular, non-uniform thickness [11] slicing can be realized. The possibility of a variable thickness in the layer extension can reduce the total number of layers, the support volume, and the manufacturing time, also increasing the surface finish and mechanical performances of the final product [4].

In particular, non-uniform slicing refers to non-parallel planar layers and the slicing direction is changed at each layer [11]. This approach can be implemented by varing the slicing direction for each layer to optimize some objective function (e.g., minimize the overhangs or reduce the staircase effect), as shown in Fig. 1b. After collecting the normals of the CAD surfaces, the minimal enclosing crown algorithm is applied [11]. The vectors are reported in a Gauss Map, so they are represented as a set of points. A spherical crown with a minimum-radius bottom surface that contains all the points is found on the sphere surface. The normal vector to the bottom surface of the minimal enclosing crown is the optimal slicing direction. However, the minimal enclosing crown algorithm can be unstable for simple geometries originating few distinct normal directions.

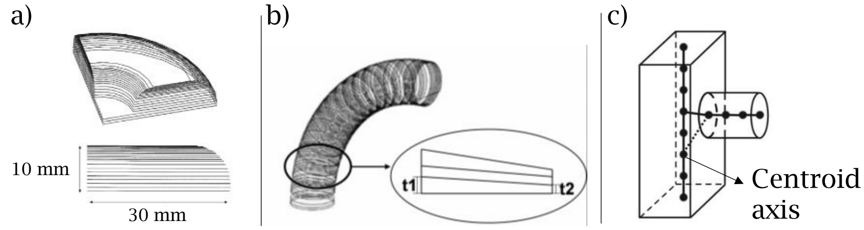

Fig. 1: Reviewed algorithms: a) Adaptive slicing [9]; b) Non-uniform slicing based on minimal enclosing crown algorithm [11], taken from [6]; c) Non-uniform slicing based on centroid axis algorithm [8].

Alternatively, non-uniform slicing can be driven by the centroid axis [8] or 1D medial axis [10] of the input geometry (see Fig. 1c). In this case, the centroid axis can be used as a dorsal curve of slicing, defining curved trajectories. However, extremal or bulky portions, such as spheres, are often not properly captured. Also, the medial axis computation depends on the quality of the mesh and could be demanding [1].

Non-uniform slicing algorithm can increase the surface finish of curved geometries, minimizing the overhangs as the slicing direction is constantly adapted to the geometry. Nevertheless, supports are still required for high curvature portions [6]. Moreover, due to technological limits, the layer thickness must be bounded to a specific range. So, this paper presents a novel slicing strategy to obtain non-uniform layers. This approach is a part of the framework presented in [7] and it can be applied after the volume decomposition phase [6], guaranteeing a further step to process general CAD geometries. In particular, the framework can adapt to different CAD features, applying the required slicing options.

Main idea

This paper presents a slicing approach algorithm to process geometries based on the part shape and considering specific manufacturing limits.

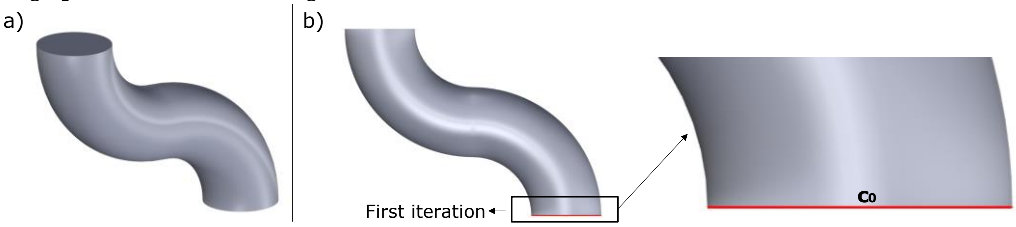

Fig. 2: Non-uniform slicing algorithm: a) Input geometry; b) First iteration of slicing.

The inputs of the algorithm are the initial geometry (see Fig. 2a), a reference layer height (*hLayer*), the maximum and minimum thickness limits that can be obtained with the selected technology (*hMax* and *hMin*). After placing the part on an initial support plane, the slicing begins by intersecting the first plane ($planes_0$) with the geometry. So, the first curve (c_0) is obtained which corresponds to the path of the first layer (see Fig. 2b).

c_0 is sampled along its length at a fixed distance to obtain a set of points. Normal vectors to the processed geometry are computed for each point, as depicted in Fig. 3a. The vectors are collected in a unit Gaussian Sphere, so that each vector is represented as a point on the sphere (see Fig. 3b). The plane that best fits this set of points is calculated (*fitPlane*), as shown in Fig. 3b. The normal to the *fitPlane* identifies the new slicing direction d_0. The origin of $planes_0$ (O_0) is moved along the d_0 by a quantity equal to the imposed layer height, creating a new point O_1. Then, the plane $planes_1$ with origin

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O_1 and normal d_0 is created, as shown in Fig. 3c. The next curve c_1 is obtained by the intersection of the initial geometry with $planes_1$.

After, the plane *bBoxPlane* is defined which is oriented so that it lays on $planes_0$ but its x axis is aligned with the rotation axis between $planes_0$ and $planes_1$, i.e. *xAxis* (Fig. 3d). The bounding box of c_1 aligned to the plane *bBoxPlane* is then computed, and the maximum and minimum values of its Y and Z domain are calculated (respectively *yMin*, *yMax*, *zMin* and *zMax*). The extremes of the Z domain correspond to the maximum and minimum thickness required to manufacture the layer. When the maximum and minimum values exceed the imposed limits, a translation and/or a rotation are applied to the $plane_1$.

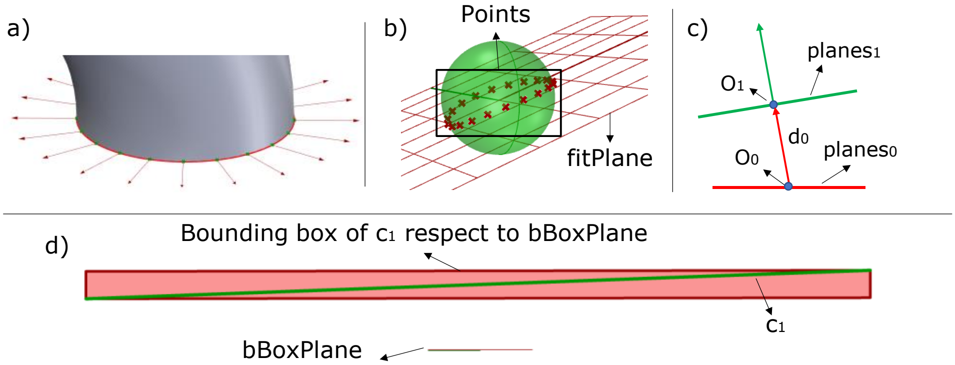

Fig. 3: Non-uniform slicing algorithm: a) Surface normal of the input geometry delimited by c_i and c_n; b) Collection of surface normals in a unit sphere and fitting of a plane; c) Evaluation of the bounding box aligned to the fitting plane.

In particular, the translation is applied when the difference between *zMax* and *zMin* is lower than the difference between the imposed limits *hMin* and *hMax*. This is because a simple translation may be enough to bring the required bead thickness to the limits. If *zMax* is greater than *hMax*, the $planes_1$ is translated by a distance equal to the difference between *hMax* and *zMax*. If *zMin* is lower than *hMin*, the translation distance is equal to the difference between *hMin* and *zMin*. On the other hand, the rotation is required when the difference between *zMax* and *zMin* is greater than the difference between *hMax* and *hMin*. In this case, the d_0 is rotated along the vector which is perpendicular to both n_0 and d_0. A new $planes_1$ is calculated with origin equal to O_1 and normal equal to the rotated d_0.

A new bounding box is calculated, and its Y and Z domains are analyzed again to be sure that the new sectioning position leads to acceptable manufacturing limits. The processing time is strongly reduce compared to the algorithm presented in [6]. Once $planes_1$ is determined, it is intersected with the initial geometry to obtain c_1, such defining a non-uniform layer as in Fig. 4a. Finally, the algorithm proceeds identifying the following $planes_i$ and c_i, repeating the procedure until all the geometry is sliced. A typical result is presented in Fig. 4b.

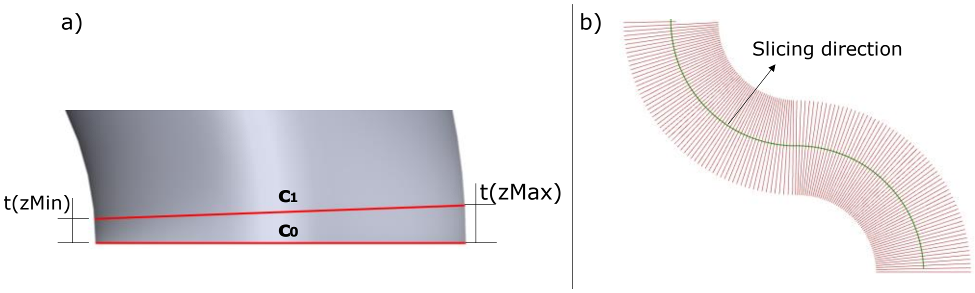

Fig. 4: a) Single non-uniform layer; b) Final result of the slicing process.

The algorithm has been developed in the Rhinoceros 7 CAD system by using the plug-in Grasshopper® for visual programming, as shown in Fig. 5. In particular, the plug-in GHPython was implemented to develop the slicing routine, integrating Python scripts with the Grasshopper® library functions.

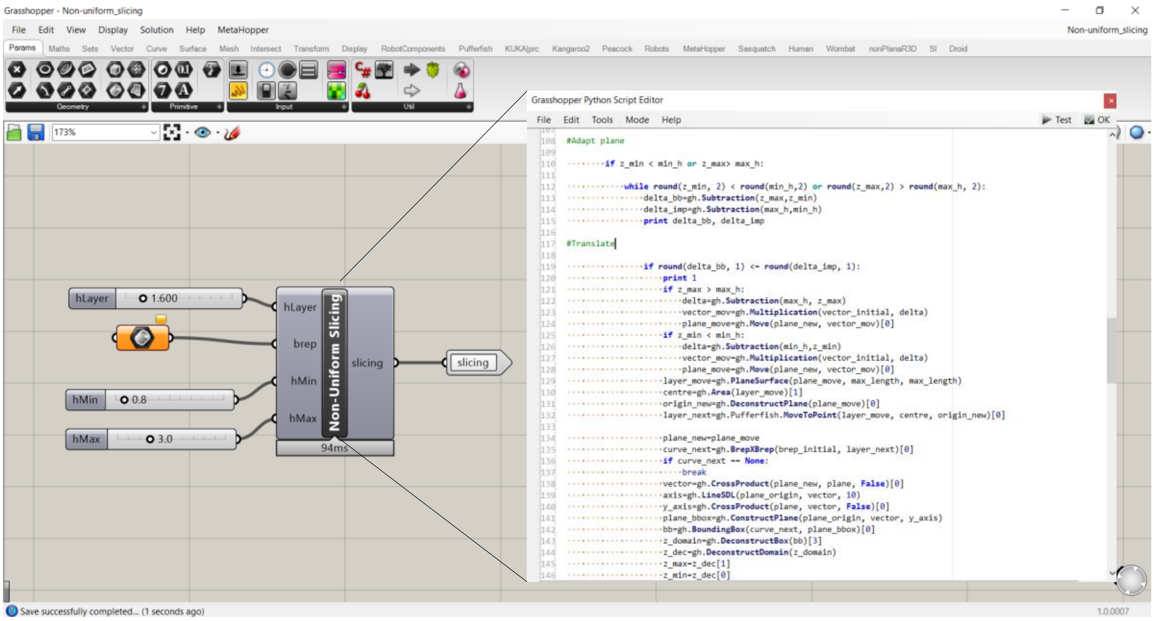

Fig. 5: Developed algorithm in Rhinoceros 7 and the plug in Grasshopper®.

The developed plug-in allowed to test various parts to validate the approach and evaluate the influences of the layer thickness limits to the slicing result, as shown in Fig. 6.

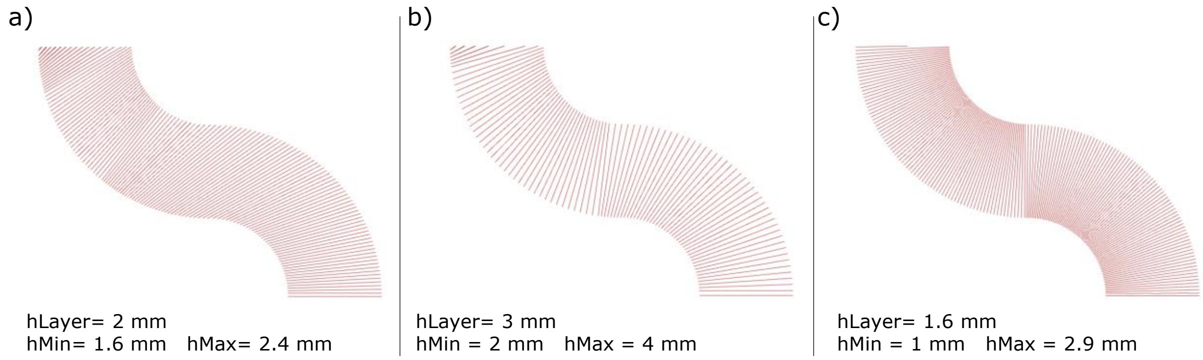

Fig. 6: Non-uniform slicing applied to the same geometry but with different manufacturing limits.

<u>Conclusions:</u>

Non-uniform slicing is a powerful tool to process curved and complex geometries. It is beneficial to increase the adhesion of layers, the surface finish and mechanical properties of the final part, also reducing the need of supports.

This paper introduces an algorithm for non-uniform slicing based on the shape of an input CAD geometry. The algorithm collects in a unit sphere the surface normal vectors of the portion of the input CAD geometry bounded by two consecutive layers. Unlike other works, the fit plane of these points is used as a new plane to perform the intersection with the input CAD model, resulting in a non-uniform layer.

As future work, specific hardware solutions (i.e., extruder/welding torch attached to a manipulator) must be implemented. Also, an extensive experimental campaign is mandatory to connect the process parameters to the desired layer height. In fact, it is necessary to continuously adjust the process parameters to obtain different layer heights, allowing for non-uniform slice thicknesses. Also, an infill strategy for the algorithm must be explored. Finally, the robot targets must be accurately defined to be followed and reproduce the required paths.

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