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RESEARCH

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A new algorithm for optimal process parameters based on minimum building time in additive manufacturing

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Abstract

Background: Additive manufacturing method is used for manufacturing of solid three-dimensional parts. It requires less human efforts and manufacturing time for parts is less. Different process parameters such as layer thickness, building orientation, infill type, and infill percentage affect the building time, model cost, mechanical properties, and surface roughness. The presented paper develops an algorithm for adapting layers and generating tool-paths. This algorithm can improve the fabrication efficiency and geometrical accuracy in the additive manufacturing (AM) of complex models. The proposed algorithm consists of three modules that identify the optimal process parameters, named as part building orientation, layer thickness, strategy type for internal filling, and slope of the tool-path.

Results: The input is the PTS file that contains the points of the layers contour of the computer-aided design (CAD) model. All the modules for the proposed algorithm were implemented using the MATLAB R2019a programming language software. The main finding results showed that the fabrication with an adaptive layer thickness was more time-efficient. The build time was reduced up to 47.3%. The developed tool-path generation strategies (contour offset and zigzag line tool-path) can effectively balance the AM surface quality and fabrication efficiency requirements.

Conclusion: In this research, the AM users can benefit by saving the cost and time. The parts were fabricated with a high degree of accuracy, and the surface finish was suitable for determining the optimal process parameter.

Keywords: Additive manufacturing, Adaptive layer thickness, Model orientation, Fabricating efficiency, Geometrical accuracy, Filling strategy

1 Background

Additive manufacturing (AM) is a general term for innovations that help in manufacturing tangible parts, especially from the design information sources. AM processes are gaining popularity in several industries because of how complex parts can be manufactured. However, achieving part quality and minimizing the build time are the most crucial challenge faced in AM [1–4]. AM has helped create businesses to satisfy customer demands for persistent and fast fabrication changes [5]. The operations of AM are effortless, and control is required to manufacture parts with locally controlled properties. However, AM forms have their inadequacies related to precision, surface quality, building time, quality, and so on [6]. Consequently, it is vital to determine the strategies' inadequacies and distinguish the controllable parameters for the advancement of part quality and manufacturing effectiveness. Therefore, the proposed paper focuses on the part building strategy by choosing the optimum building parameters in line with the part quality and fabricating efficiency [7, 8]. In this study, an adaptive layer

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thickness module is used to determine the suitable thickness of each layer for adjusting the geometrical accuracy and constructing the proficiency amid the creation of AM forms. The proposed adaptive layer thickness module's basic principle is to compare all the points on the x and y coordinates for two contours located on adjacent slices. If these points match in both slices, the first sliced layer is deleted from the bottom; this step means merging between two consecutive layers. This process is repeated in the next layer and so on until the maximum layer thickness is reached. The tool-paths help manufacture the zone along the boundary of each layer so that the complicated parts' geometrical quality is improved. Two styles of tool-path generation strategies (offset contour and zigzag paths) were developed to fill the inside area of every layer of the complex model and enhance the building efficiency. Moreover, an inclined degree of zigzag paths was created to advance optimize the construct time by choosing the ideal incline degree of the AM nozzle head along the zigzag paths that decrease the minimum target's build time. The manufacturing time may be a significant criterion that affects the fabrication efficiency in building a physical part for various AM systems. Numerous papers have been published in this area. In [9], the authors presented a unique framework for large format additive manufacturing, for generating a globally continuous tool-path for both solid and partial infill designs. Outward contour and double offset approaches are used to generate smooth curves as the principal volume-filling paths for solid infill, with extending zigzag lines from the closest contours covering the remaining empty spaces. Then, using the depth-first-search technique, a contour layer-wise link is made to create a globally continuous path. In [10], by combining physics-informed computer simulation models with actual observations, this paper proposes a unique process design optimization approach for additive manufacturing (AM). The suggested framework is utilized to improve process parameters in the fused filament fabrication (FFF) AM process, such as extrusion temperature, extrusion velocity, and layer thickness, in order to reduce variability in the geometry of the manufactured item. In [11], the authors investigated the staircase error between the sliced layers of the contour. The volumetric error was then deduced from the mathematical model. Based on the established model, an adjustable slice orientation approach was applied to decide the optimum slice orientation with the least volume difference in AM. In [12], the researchers created an orientation framework for solid models by considering the volumetric error in models. In one calculation, the part was sliced with even planes, and the volumetric error of each layer was computed using complex shapes. An algorithm was also developed to read the STL file, remove the unnecessary data, extract the desired coordinates that described the entire computer-aided design (CAD) model, and delete the file's redundant coordinates [13]. The developed algorithm is used to control the CAD model's orientation by any angle and slicing the oriented CAD model by the specified layer thickness. A generative handle arranging framework was created by [14] for the RP process's parts. The proposed handle arrangement includes determining the ideal for orienting the show using the correct support structure; therefore, this arrangement provides an intelligent slicing strategy (e.g., coordinate or adaptive) to decrease the build time by keeping the geometry cusp stature errors in control. Inclining build edges are considered for a better approximation of the surface model. Researchers have developed an inter-algorithm for the optimum design direction for parts [15]. The authors determined the build time for the subsequent orientation and then tested the stability after the primary objective function's value, part accuracy. The procedure was replicated before the orientation was found, which met the accuracy of the part with the minimum build time. In [16], the authors established optimum design guidance for adaptive slicing while considering other aspects such as time of construction, accuracy, and part stability. The authors used the genetic formula to determine the minimum thickness of the layer required for a cusp tolerance stature. The laser beam scanning mechanism of stereo-lithography has been studied to assess the efficacy of the connection used in literature to estimate the build time. In [17], the authors discussed a method to examine the tribological process of the steel. Within the introductory arrange of the grating wear handle, the micro-topography of steels radically changes until it comes to a stable state. This alter can be depicted by distinctive strategies. One of the methods is the characterization with the assistance of roughness parameters. In this paper, approved simulation algorithm has been utilized to predict the adjustment of the roughness parameters. Fabricated micro-topographies with same arithmetical mean height can be modeled to the wrecking with the assistance of rough worn-micro topography. The most roughness characteristics, such as arithmetical mean height, root mean square roughness, skewness, and kurtosis adjustment, were found to be strongly influenced by the production technology. In [18], the authors stated that conventional 3D printing is based on stereo-lithography or standard translation language models, which contain much repetitive information and have low accuracy. This paper proposed a slicing and support structure generation algorithm for 3D printing directly on boundary representation (B-rep) models. To begin with, surface slicing is performed by efficiently computing the crossing point bends between the faces of the B-rep models and each cutting plane. Then, the normal of the B-rep models is utilized to distinguish where the support structures ought to be found and the support structures are produced. The algorithm was testing and it appears a proficiency during the experiments. In [19], a new algorithm for 3D-printing innovation was proposed to produce large-scale objects, particularly A-shaped mankind, or 3D human body scan information. Most of the traditional 3D printers have a finite printing volume, and it is the users' work to convert the target object into a printable measure. In this work, a programmed three-step division procedure was connected to the raw manikin work information until the final pieces had a smaller measure than the 3D printer's greatest printing volume, which is called "beam length." The human body feature point data were received for design and textile analysts to effortlessly indicate the specified cutting positions. A basic bounding box, particularly situating bounding box, and modified Boolean administrator were proposed to extricate the specified sections with computational soundness. The proposed method was connected to graphically synthesized puppet information, and 1/8, 1/4, and 1/2 scale mankind were effectively printed, minimizing the sum of support structure. In [20], the paper stated that The Standard Tessellation Language(STL)model is the common file for the additive manufacturing (AM) geometric model, but it has a few drawbacks, such as huge errors of the geometric model depiction, the simple misfortune of topology data, information duplication, huge save sizes, and so on. Pointing at these issues, a direct slicing algorithm based on a Standard for the Exchange of Product Model Data (STEP) model was proposed. For the parts composed of essential types of surfaces such as boundary bends, circular surfaces and round and hollow surfaces, the conventional geometric strategy was utilized to calculate the crossing point. For the parts with complex surfaces, the three-dimensional models were depicted based on Non-Uniform Rational B-Spline (NURBS) surfaces. The NURBS surfaces were layered employing a discrete following algorithm, the following beginning point was decided, the crossing point line between the digression plane and each NURBS sub-surface was gotten, and the closed layer form was shaped. At last, the slicingsimulations and printing tests of solid parts were carried out utilizing the coordinate slicing algorithm based on the STEP model. It was shown that the dimensional exactness and surface quality of the printed parts from this calculation had been essentially progressed. In [21], the authors present (1) a strategy that produces continuous paths to fill 2D polygons with a hybrid zigzag and contour design with any direction and line division, which extends an algorithm that breaks down the 2D region to be filled into raised zones, overcoming its confinements to create less sub polygons in certain cases, (2) a strategy to connect the sub polygon directions such that a continuous way that fills the total polygon is obtained, and (3) a publicly accessible dataset containing (a) a set of 2D polygons that are important to test the execution of the algorithms and (b) the results of filling those polygons with the proposed technique. Results appear that the proposed strategies deliver satisfactory results for the polygons contained within the evaluation dataset, counting a couple of showings of real 3D prints with the produced trajectories. Advance work is required to expand the strategy to deliver reasonable solutions for polygons with curved gaps.

Although these previous efforts provide useful contributions to the field, they do not provide an algorithm to determine the most effective process parameters from direct slicing to minimum building time. These studies do not clarify and provide point-by-point calculations to help analysts make computer programs that check the different AM parameters without any experimental work. This paper presents an algorithm for identifying the optimal process parameters, such as part building orientation, layer thickness, strategy type for internal filling, and the slope of the tool-path that supports a minimum building time approach. This algorithm will help AM users create AM physically complex models with high levels of fabrication efficiency.

2 Methods

The proposed algorithm consists of three modules that help obtain optimal process parameters, such as part building orientation, layer thickness, strategy type for internal filling, and tool-path slope. These modules improve the fabricating efficiency and geometrical accuracy, especially for complex product models. This method assumed that the machine supports the adaptive layer thickness option. An overview of the methodology for the algorithm is given below.

1. The algorithm has an adaptive layer thickness module for the uniform direct slicing model to improve

the fabrication efficiency by minimizing the building time. The suggested module starts by identifying the part features and divides the model into regions according to its geometrical shape. Then, the module determines an appropriate build layer thickness separately for every region.

2. Path planning modules are developed to obtain two internal filling tool-path strategies: contour offset and zigzag paths. The most influential interior and exterior tool-path strategies are then obtained to fulfill the accuracy and efficiency requirements.
3. The building time is defined for recognizing the most viable build-up direction, tool-paths filling technique (contour or zigzag paths), and the incline degree of the zigzag device (to fill the interior of each layer) can be determined to help minimize the build time.

All the other modules for the proposed calculation were executed using the MATLAB R2019a programming language program. The following sections describe the strategies used.

2.1 Model preparation module

As presented in [1], the proposed uniform direct slicing process was applied to the CAD model after the merger with the constructed guided column. A group of intersection points was obtained on the boundary between the horizontal planes. Therefore, the model created a physical part. The output PTS file contained the intersection points of the CAD model contours and the coordinates of the intersection points that represented the guided column, as shown in Fig. 1. In this section, only the model's coordinate points will be extracted by implementing the following two stages. This section describes the experimental results, interprets these results, and concludes.

2.1.1 Column removing stage

First, the slices at the bottom and the last slices at the top need to be discarded; otherwise, they will build undesirable layers in the physical part, representing the upper and lower parts of the guided column. The removal process occurs by creating a module using the MATLAB software used for searching the location (X–Y coordinates) of the first point in each layer along the column. This location is constant and known from the refinement module, as shown in [1]. The proposed module finds and deletes the coordinate of this point in each layer from the whole file. The other remaining issues of the guided column in the same layer are deleted; these points were distributed uniformly on the contour. The number of these points is not constant, but they vary according to the degree of accuracy required by the user.

2.1.2 Rearrangement Z-values stage

Also, the CAD model was merged with the guided column. The CAD model was located at a high level from the building platform ($Z=0$) because the model's coordinate system was coincident with another coordinate system of a rotating process located in the middle of the column. After removing the column parts, all the point

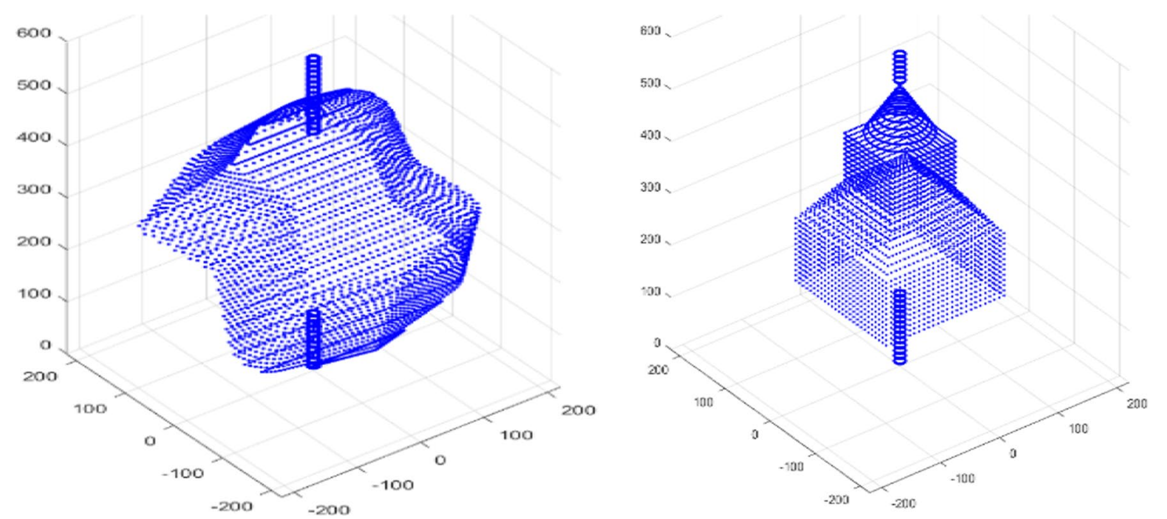


Fig. 1 Examples with the guided column after the slicing process in the form of points. The output PTS file contained the intersection points of the CAD model contours and the coordinates of the intersection points that represented the guided column

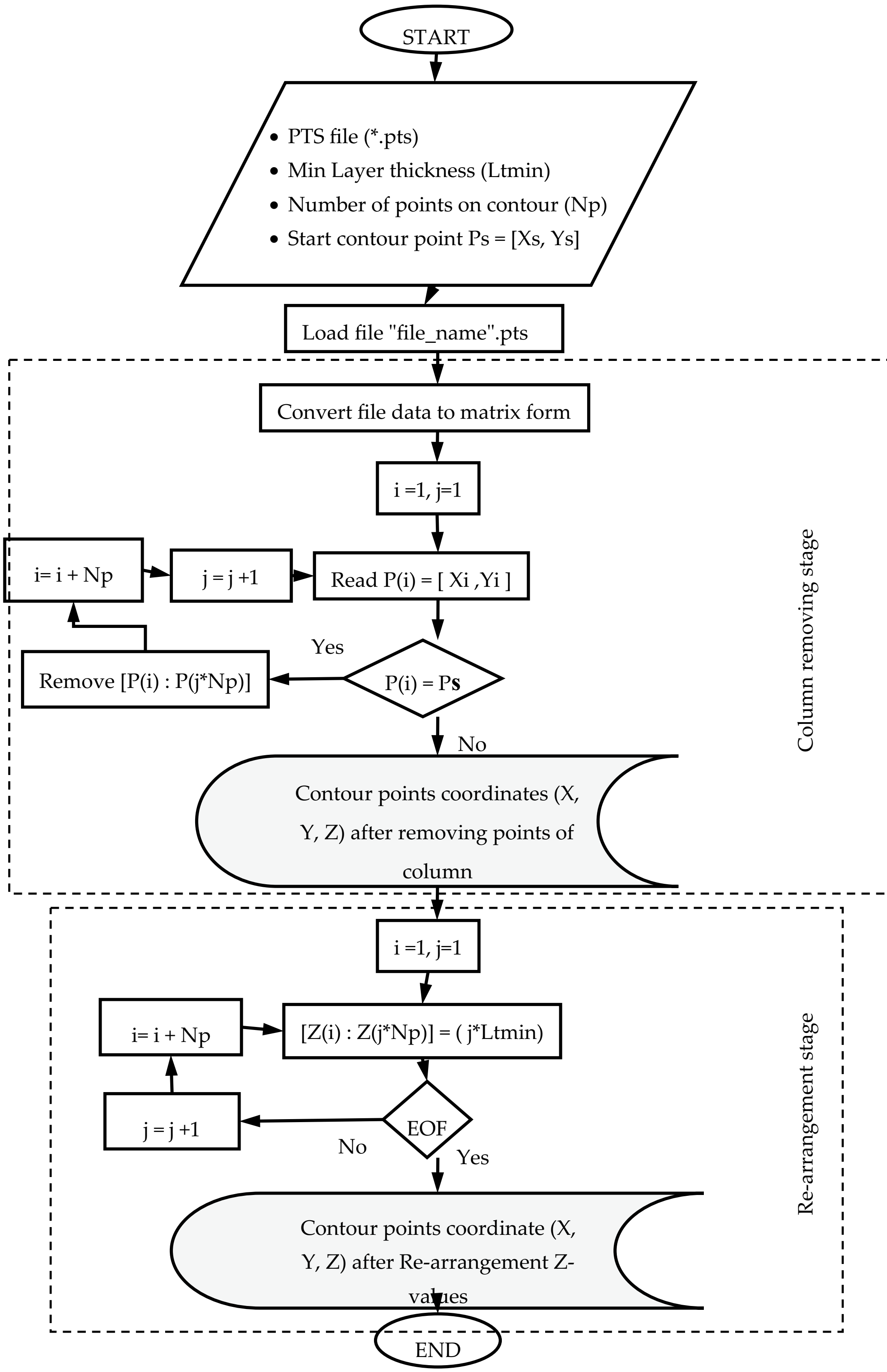


Fig. 2 Flowchart for the proposed model preparation module. The figure shows the two stages of model preparation which called Column Removing Stage and Rearrangement Z-Values Stage

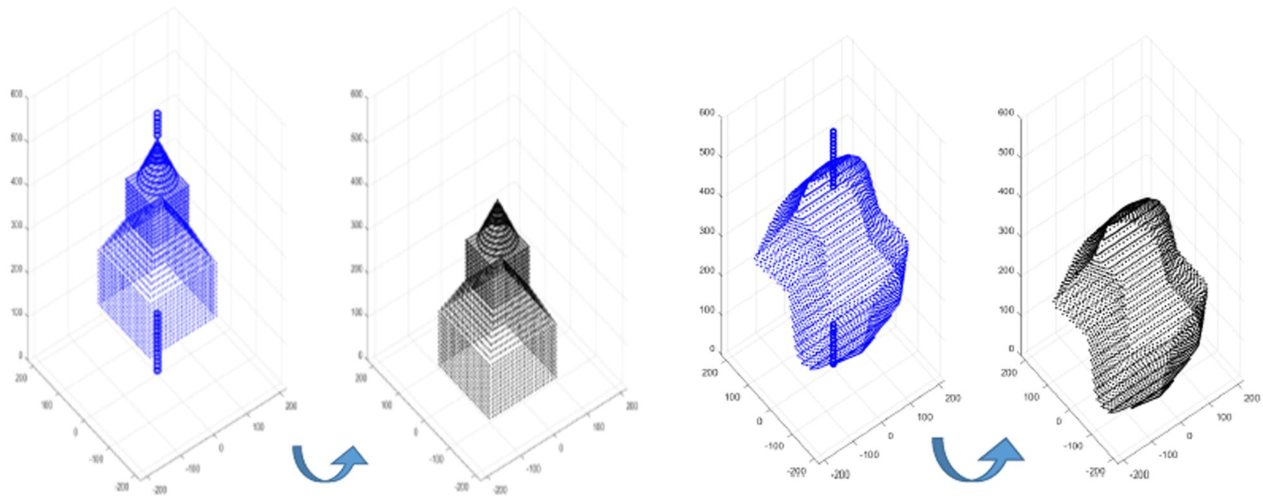


Fig. 3 Examples after applying the model preparation module

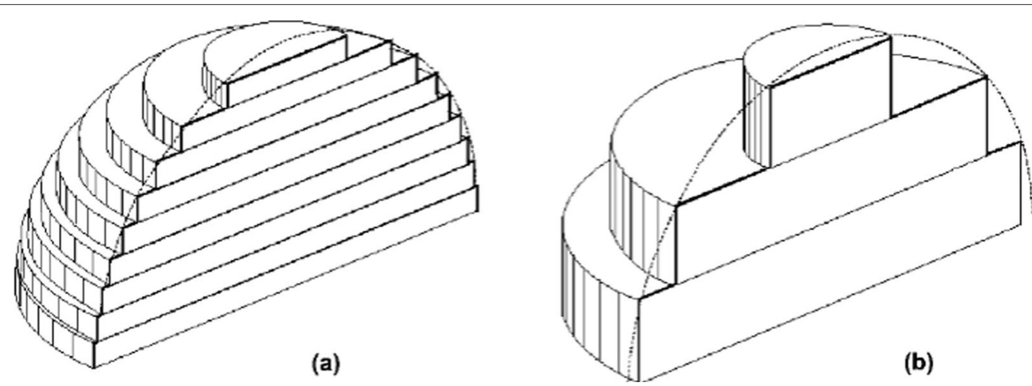


Fig. 4 Comparison of staircase inaccuracies because of thin and thick layers. **a** Thin layers better approximate the surfaces; **b** thick build layers poorly approximate complex surfaces. The figure demonstrates how the staircase inaccuracies in thicker layers are considerably higher. In contrast, the use of thin layers helps to make the surfaces cleaner and more detailed. Source: Sabourin, 1996; Sabourin et al. (1997), Reference 22

coordinates in each layer in the PTS file needed to be rearranged for all Z-values. The arrangement starts in the Z-axis from the minimum layer thickness. Thus, the PTS file contains only the model's point coordinates, representing its contours after implementing the proposed uniform direct slicing process. The detailed steps of these two stages are shown in the flowchart (Fig. 2). Figure 3 shows both the illustrated examples after applying module No.3.

2.2 Layers adapting module

The design of a 3D CAD model with 2D layers, as shown in the previous sections, would provide an estimated representation of the initial surface geometric because of their impacts on the staircase. Figure 4 demonstrates how the staircase inaccuracies in thicker layers are considerably higher. In contrast, the use of thin layers helps to make the surfaces cleaner and more detailed. Consequently, the model quality is improved by decreasing the construct layer thickness. Therefore, thin layers have been used in the previous uniform direct slicing approach; however, reducing the build layer thickness leads to a rise in the fabrication time. Therefore, adaptive slicing is preferred because both the thick and thin layers have comparable building times and can save fabrication time. Adaptive slicing may reduce the building time and maintain model precision by minimizing the staircase error when deciding the appropriate thickness for each sliced layer. Many researchers from worldwide have continuously developed new algorithms to apply the adaptive direct slicing concept. The most adaptive direct slicing methods assisted the cusp height concepts for testing the staircase effect. In this study, a replacement adaptive direct slicing technique was proposed to maintain surface quality without a user-specified cusp height. This new technique will minimize the time needed to decide the thickness of the layer that matches the surface standard. The concept is that a 3D CAD model's surface complexity can be evaluated using a PTS file. This is the adaptive direct sliding approach. The layer thicknesses are determined using the bottom-up technique, which respects the 3D model's sophistication. The layer thicknesses are typically distinct values that are prefixed by the consumer and are constrained by the manufacturing capability of the particular AM process [Lmin, Lmax]. Layers are usually preferable with the largest thickness. This ensures that there is a maximum distance between the two sliding contours. However, for a single layer, only full-thickness should be recommended. The simplicity of a layer is so defined that the contours up and down are the same. The layer (i.e., no-slip exists) is called simple if its two contours are the same. If not, its thickness has to be reduced to a minimum thickness of the layer to reduce the phase's impact. A contrast of the points X and Y coordinates among the two contours on adjoining slits determines the basic principle of this adaptive module. If the two slices meet these coordinate points, the points on the first slice will be removed from the bottom. For lack of a staircase effect on a 3D view, Fig. 5 shows the illustrative example (1) before and after applying the proposed adapting approach. The details are shown through a flowchart in Fig. 6.

2.3 Tool-path filling strategies module

A tool-path is that the trajectory of nozzles or print heads used during the AM process fills the inside of every AM layer. This is an essential factor that affects the part quality and efficiency. After creating the intersecting planes in each Z increment and generating the points that indicate the form of every contour, the points should be connected to create a continuous path. The proposed algorithm can generate contour tool-paths to fabricate the area along the boundary of every AM-sliced layer.

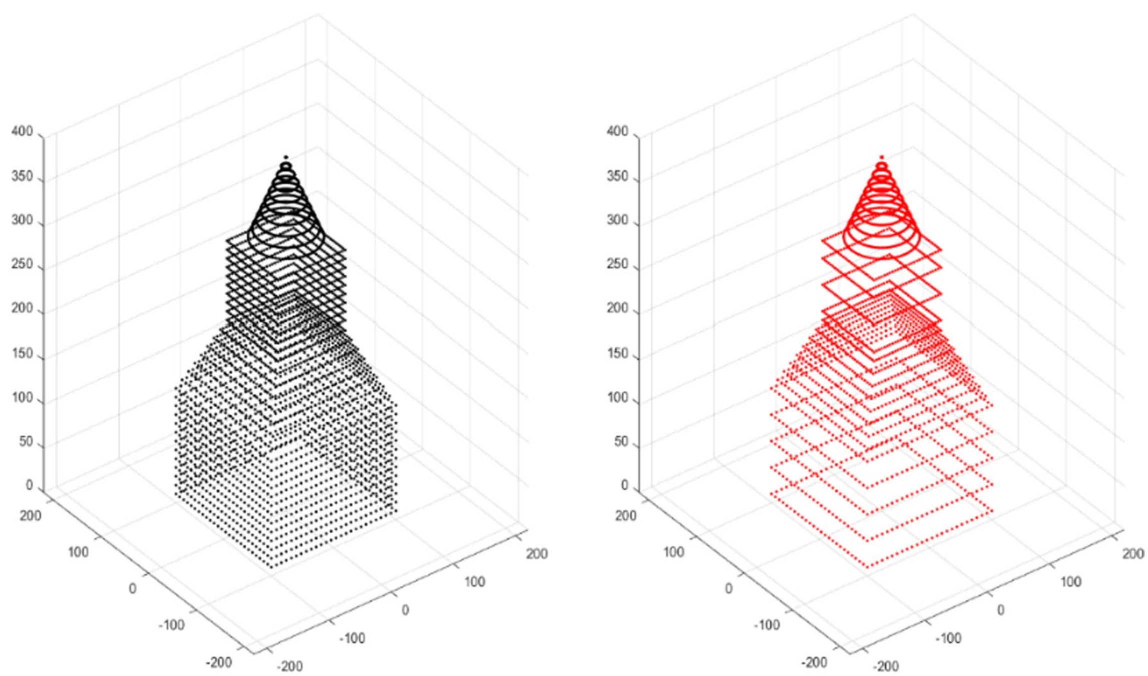


Fig. 5 Example (1) was adaptively sliced using the proposed module. The figure shows the illustrative example (1) before and after applying the proposed adapting approach

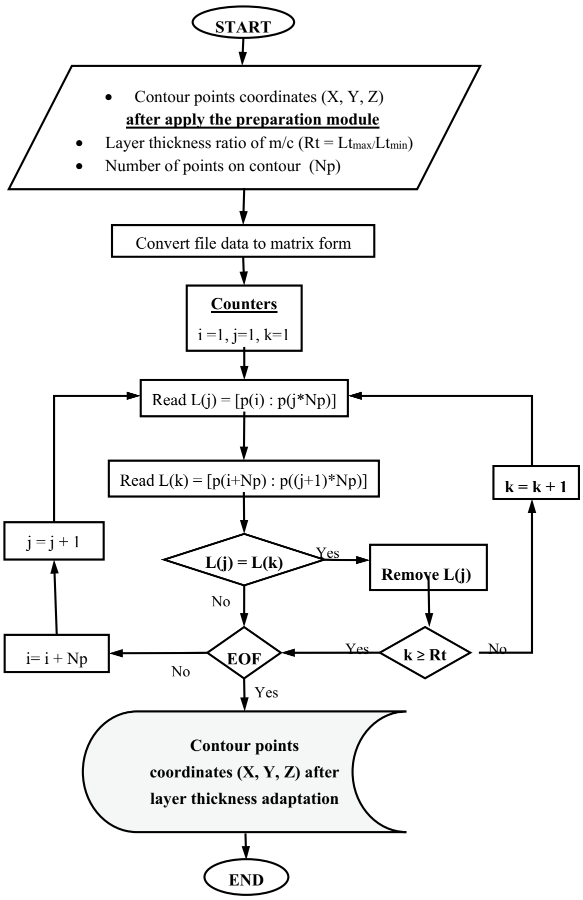


Fig. 6 Flowchart of the proposed adaptive slicing approach

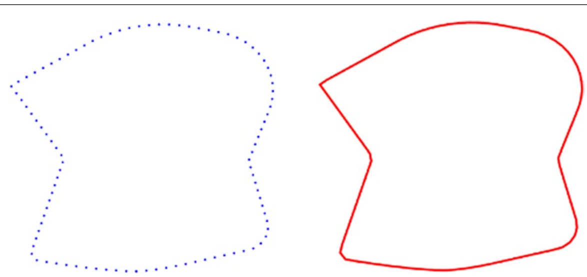


Fig. 7 Layer boundary tool path generated from the layer coordinates points in example (2). The proposed algorithm can generate contour tool-paths to fabricate the area along the boundary of every AM-sliced layer. This can scale back surface errors and improve the geometrical quality of models

This can scale back surface errors and improve the geometrical quality of models (Fig. 7). There are many tool-path strategies developed for AM processes for the inner area to form fully solid parts, such as zigzag, contour offset, spiral, and partition patterns. The following sections present the two proposed tool-path strategies to build the interior area of the commonly used models in AM. These strategies are contour offset tool-paths, which are also known as contour parallel tool-paths and zigzag pattern tool-paths.

2.3.1 Contour offset tool-path strategy

Contour offset tool-path generation is a filling strategy that can successfully address the part quality problem by following the boundary contours' geometrical trend. In this tool-path pattern, a series of offset contours of the layer boundary was created after the layer's contours were first generated. The AM nozzle/print head traveled along with these offsets one by one until the entire layer was fabricated (see Fig. 8).

Various contour offset patterns were investigated in previous studies. Two essential factors needed to be considered comprehensively within the proposed contour offsets tool-path strategy: nozzle diameter (or print head diameter) and the linking of tool-path offset points. Consistent with these factors, a centroid of every layer was determined by the MATLAB tool functions. The number of offsets for every point at the layer perimeter was also determined. Each offset contour contained multiple line portions, which were parallel to the indicated slant of the boundary. The proposed approach for the contour offset/parallel tool-paths strategy is explained in detail in Fig. 9.

2.3.2 Zigzag tool-path strategy

Zigzag pattern tool-path generation is the most popular filling strategy used in commercial AM machines. With zigzag pattern tool-paths, the nozzles or print heads are moved along equally spaced straight lines or "zigzag segments," which significantly reduces the number of tool passes. This space is either equal to the nozzle diameter or less than this diameter, depending on its technique. This strategy significantly improves the productivity of the AM process by reducing the required transition motions of the machine.

The zigzag pattern tool-path strategy combines the separate parallel lines into one continuous pass, created horizontally. To form a continuous path, the intersection of this horizontal family of lines with the layer boundary naturally defines the intersection points used for interconnecting the neighboring zigzag segments by moving through them and along the layer's boundary.

However, the contour accuracy for the zigzag pattern strategy is low because of the discretization errors on an edge that is not parallel to the direction of tool motion.

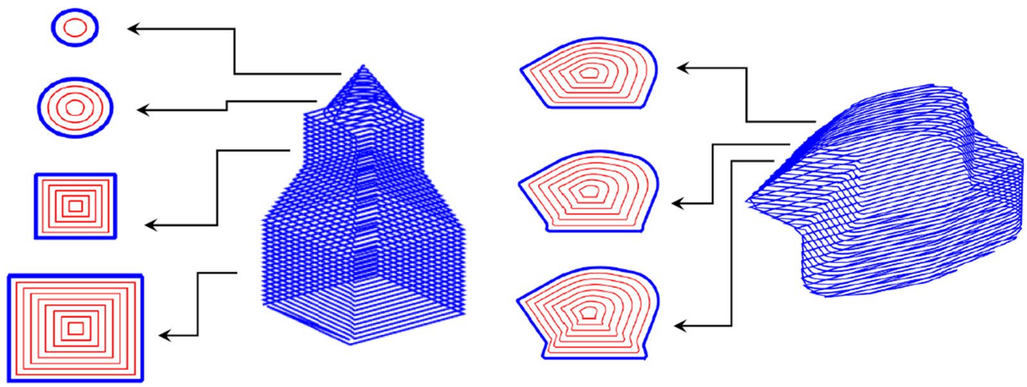


Fig. 8 Contour offset tool-paths generated by the proposed algorithm for different layers in both examples. The AM nozzle/print head traveled along with these offsets one by one until the entire layer was fabricated

Therefore, the proposed approach used one contour offset of the layer's boundary for intersecting with the straight parallel lines. After generating the first contour offset tool-paths, separate parallel lines intersected with them. The intersection points were then stored in a matrix (IPZ). For fabricating the inner area of the model, the intersection points were rearranged, and the tool-paths were then generated in step with the new positions of the intersection points within the matrix (see Fig. 10).

The proposed approach involves the following steps:

1.Read the coordinate points for each layer.

2.Generate only one contour offset of the boundary for each layer.

3.Determine the maximum and minimum coordinates of the machine's platform along both the X and Y axes; assign the maximum coordinates as Xmax and Ymax, and the minimum coordinates as Xmin and Ymin.

4.Generate an array of separate equally spaced parallel horizontal lines throughout the platform limits. The lines are separated by {D} or a ratio of it, and the overlapping effect is considered; D is the nozzle/print head diameter.

5.Intersect the lines with contour offset and group the intersected points in the IPZ array, where IPZ = [Xp, Yp].

6.Using the subsequent steps, convert the parallel tool-path lines from the one-way pattern to the zigzag tool-path filling pattern (see Fig. 11).

6.1.Read the first four points from the array IPZ.

6.2.Arrange them in new arrays (IPZg) as follows:

IPZg (i) = IPZ (1)

IPZg (i+1) = IPZ (2)

IPZg (i+2) = IPZ (4)

IPZg (i+3) = IPZ (3)

Put $i = i + 1$

6.3.Remove the first four points from the IPZ array.

6.4.Repeat the steps until i = (no. of intersected points/4).

Figure 12 shows the examples after applying the proposed zigzag tool-path's approach. Also, the rotation matrix is used about the Z-axis within the proposed approach to rotate the separate parallel lines and incrementally change the slope. The tool-paths with different degrees ranging from 0° to 75° are shown in Fig. 13.

Thus, the slope of the zigzag segments is chosen to minimize the full length of the tool-paths, which results in minimum build time. The rotation matrix that is coded using MATLAB R2019a programing language is often expressed mathematically as follows:

$$R_{z,\theta} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

The flowchart shown in Fig. 14 explains the steps followed for generating the proposed zigzag tool-path strategy in all the model layers.

2.4 Decision criteria for part orientation

This paper aims to determine the optimum orientation of the CAD model so that the part quality can be improved. Volumetric error, mainly caused by the difference between the CAD and physical modes, is used to assess the part quality. The manufacturing time could be a crucial parameter that varies with the build orientation, variety of filling strategies, and slope (in the zigzag tool-path filling). The manufacturing time also affects the cost of producing a part and the productivity of large-scale manufacturing. Calculating an accurate building time is not easy because it is difficult to think about all the building parameters, including the acceleration and deceleration of a nozzle. Therefore, the overall building time was estimated partly using geometry and major machine parameters. The building time was proportional to the

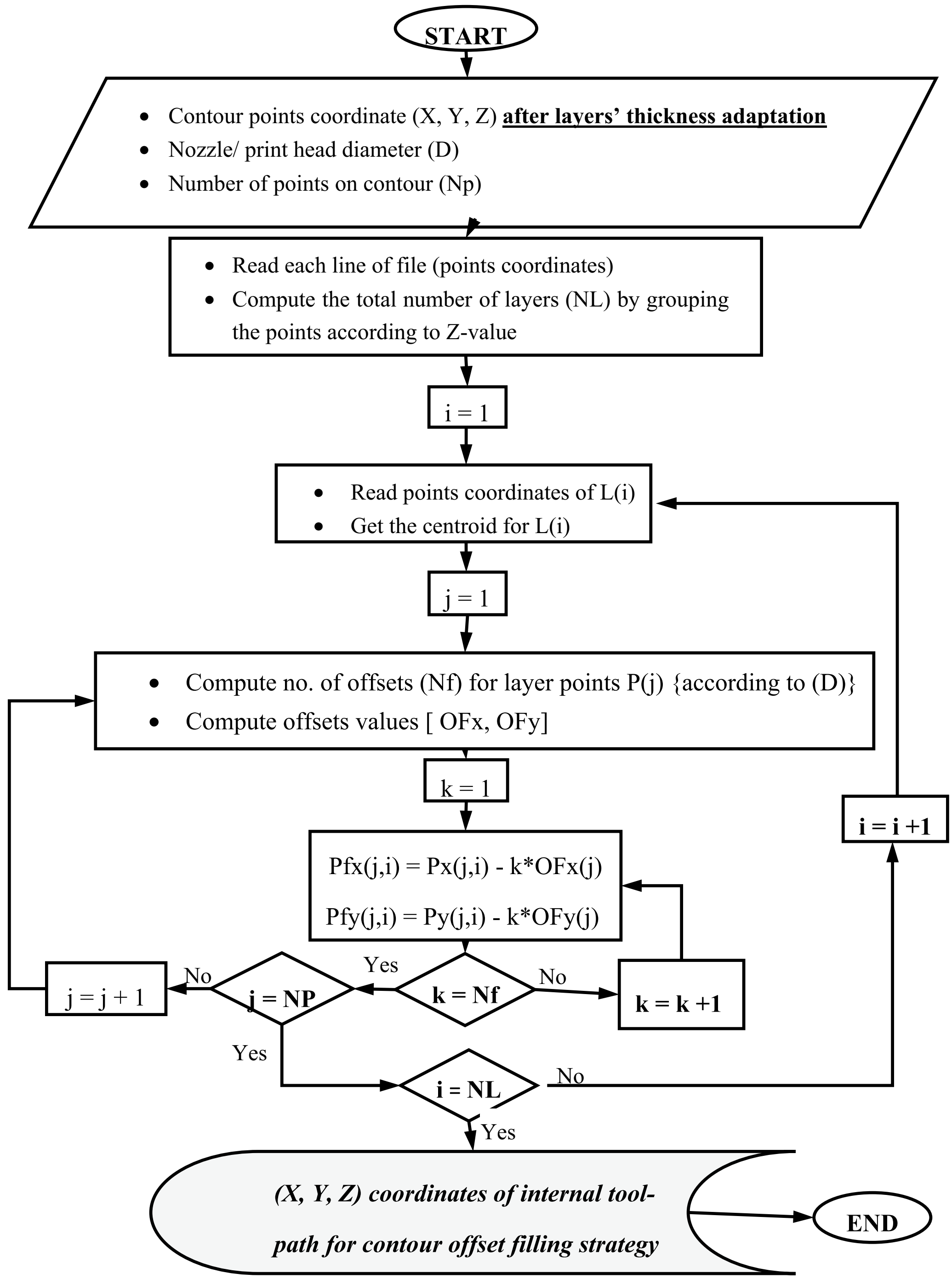


Fig. 9 Flowchart of the proposed contour offset tool-path strategy

three elements: data preparation time (Te), fabrication time (Tf), and post-processing time (Ts). Therefore, the building time was computed as follows:

$$MT = Te + Tf + Ts. \quad (1)$$

The data preparation time is often much less than the building and post-processing time, especially when

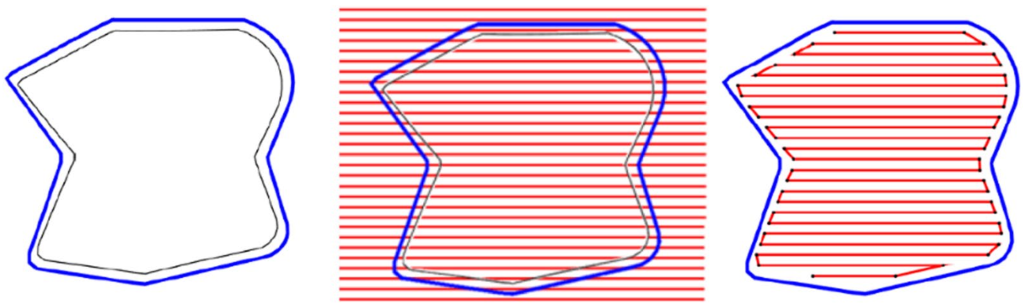
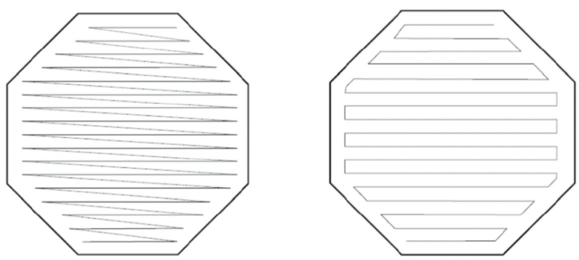


Fig. 10 Processing of the proposed zigzag tool-paths approach. For fabricating the inner area of the model, the intersection points were rearranged, and the tool-paths were then generated in step with the new positions of the intersection points within the matrix



(a) Zigzag tool-path pattern (b) Zigzag line tool-path pattern

Fig. 11 Different types of direction-parallel tool-path patterns. Using the subsequent steps, convert the parallel tool-path lines from the one-way pattern to the zigzag tool-path filling pattern

implementing the proposed direct slicing approach, saving more time. The post-processing time is related to the part geometry and the post-processing equipment used. For processes where no external support is employed (e.g., selective laser sintering and laminated object manufacturing), the post-processing of a given part is independent of the building direction. For processes where external support is also required, specific orientations may result in a greater volume of external support; therefore, a longer post-processing time is required. Nevertheless, the difference in the post-processing times for various orientations is sometimes small. Hence, the post-processing time of a part is generally relatively constant concerning the building orientation for a given AM process. The fabrication time is the sum of the layer building times; therefore, there is a delay between the layers. The following equation can be used to calculate the fabrication time:

$$T_{\mathrm{f}} = \sum_{i=1}^{n} [T_{\mathrm{w}}(i) + T_{\mathrm{c}}(i) + T_{\mathrm{r}}(i)], \quad (2)$$

where T_f, fabrication time; n, number of layers; T_w, intermediate time between processing layers; T_c, contour building time; T_r, internal building time,

It is assumed that the nozzle speed in the proposed algorithm is constant throughout the fabrication process for all the layers; therefore, a relative measure of the

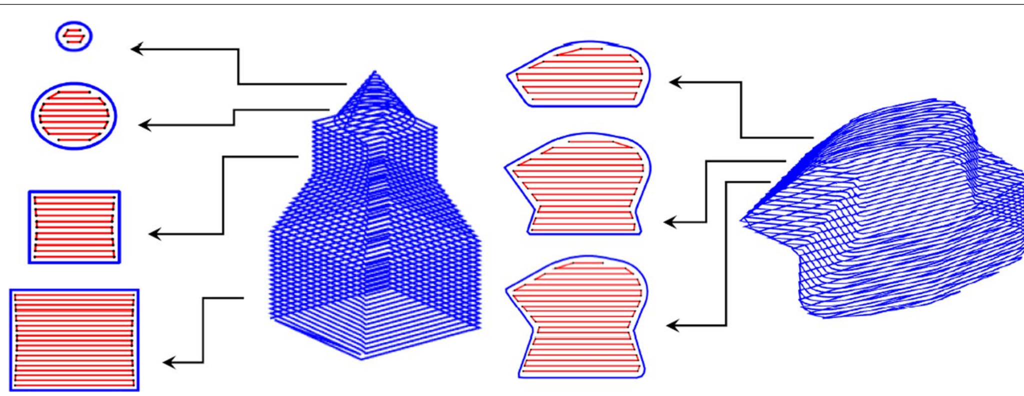


Fig. 12 Zigzag tool-paths generated by the proposed approach for different layers in both examples. Shows the examples after applying the proposed zigzag tool-path's approach

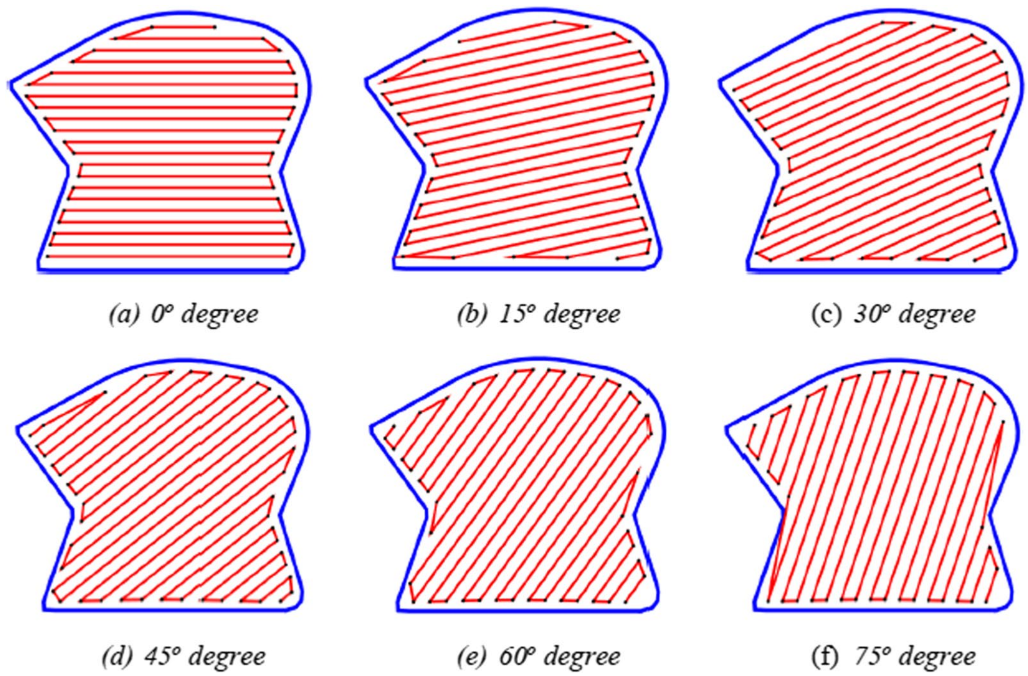


Fig. 13 Incremental of zigzag slopes for the same layer in example (2). **a** 0°; **b** 15°; **c** 30°; **d** 45°; **e** 60°; **f** 75°

fabrication time can be estimated by summing the total length to create each layer (internal and external). In addition, the nozzle has another speed for all the interval lengths between each layer. The distance between two consecutive slicing planes was determined by the slice thickness.

Equation (3) can be used to calculate the fabrication time by dividing the total length of each layer (internal and external) and the total interval lengths by each nozzle/print head speed, as follows:

$$T_{\mathrm{f}} = \frac{L}{\vartheta_{xy}} \times \frac{L_{\mathrm{t}}}{\vartheta_z}, \quad (3)$$

where ϑ_{xy} is the nozzle speed at the layer plane; ϑ_z is the nozzle speed at interval lengths between layers; L is the total length of the tool-paths in all layers; L_{t} is the total length of nozzle intervals in the Z-direction.

Here, L is given by the following equation:

$$L = \sum_{i=1}^{n} [L_c(i) + L_r(i)], \quad (4)$$

where L_r is the length of internal filling tool-path of the layer.

Also, L_t is given as follows:

$$L_t = \sum_{i=1}^{n} [L_W(i)], \quad (5)$$

where L_w is the distance between any two consecutive layers.

The part orientation that minimizes the build time will be derived from Eq. (3). Figure 15 presents the general algorithm for choosing the optimal orientation to create the part model supported by the building time criteria. The proposed algorithm was implemented using MATLAB (Version 8.1.0.604), Release2019a.

3 Results

Figures 16 and 17 show the CAD for a regular and complex shapes, respectively, in solid modeling representation, designed using PTC Creo Parametric CAD software. These models have been pre-trained. The

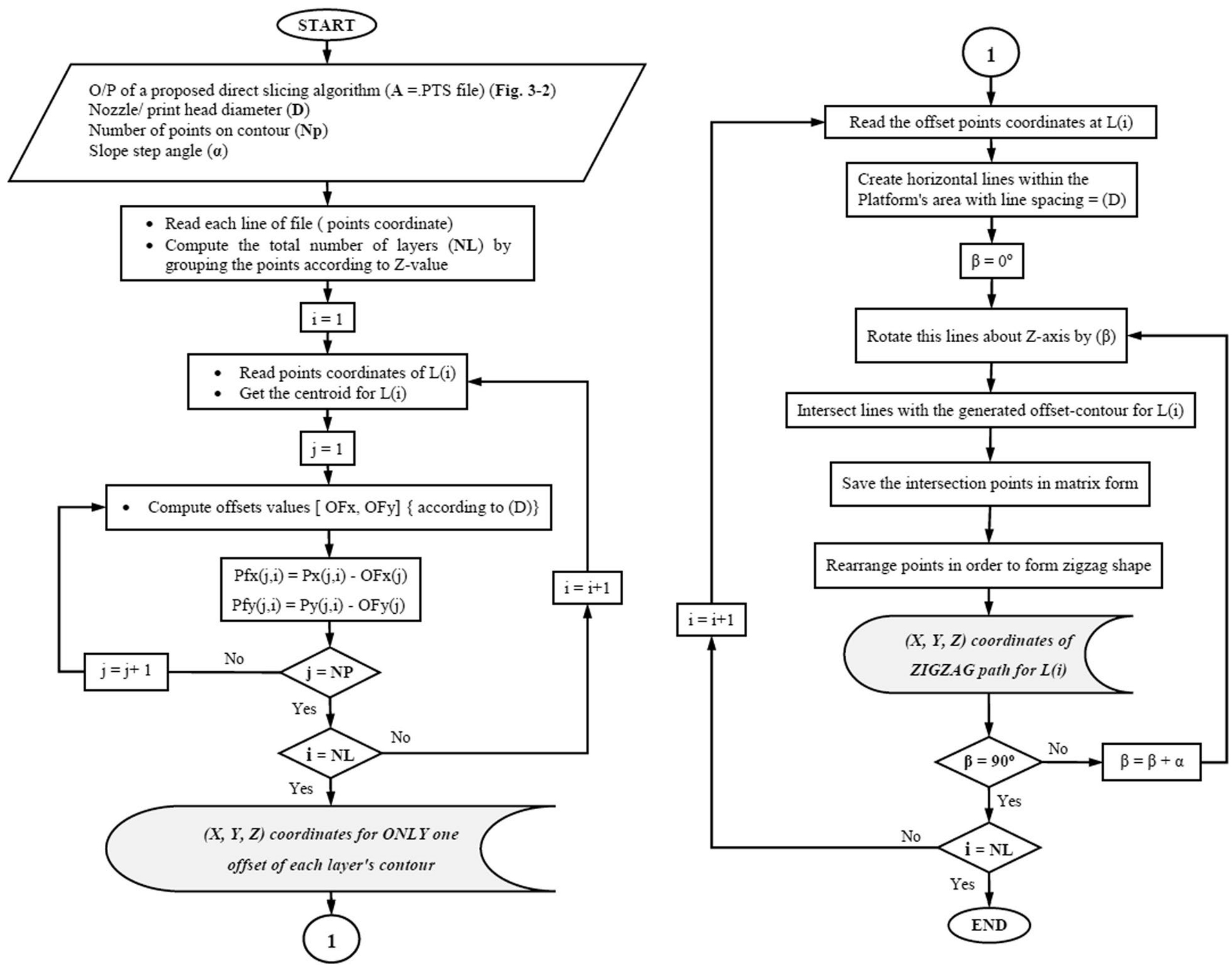


Fig. 14 Flowchart of the proposed zigzag tool-path strategy

models were split into different regions based on its geometrical shape; therefore, there were changes in the cross sections along the building direction (Z-axis). Tables 1 and 2 show the build time for the two case studies with an increment of 30° for the slope from 0° until 90°.

4 Discussion

The results show that the adaptive slicing method of the model minimizes the number of building layers compared to the uniform slicing method for all studied building orientations. In addition, above analysis shows that the layer filling with zigzag tool-path minimizes the building time rather than the offset layer contour tool-path. That is why the building with the zigzag tool-path at the slope degree of $\beta = 60°$ and orientation of 0° about the X-axis and 0° about the Y-axis has the shortest build time ever in the case study no.1 (T = 2 h and 58 min). Regarding to case study no.2, when the model still has the initial angle in the x-axis ($\theta x = 0°$) and oriented about the y-axis by 60° ($\theta y = 60°$), for which can be observed that the building time is the shortest. (T = 1 h. and 17 min), at the constant thickness (Lt = 0.5 mm). Thus, fabrication with a thick layer because of an adaptive module action during this orientation is more time-efficient. The build time was reduced up to 47.3%.

5 Conclusions

In this research, a new methodology has been presented to identify the optimal process parameters, such as part building orientation, layer thickness, strategy type for internal filling, and the slope of the tool-path (for zigzag filling strategy) AM processes. This methodology is often used for any complicated solid part using the premise of a minimum fabricating time. To accomplish the goal

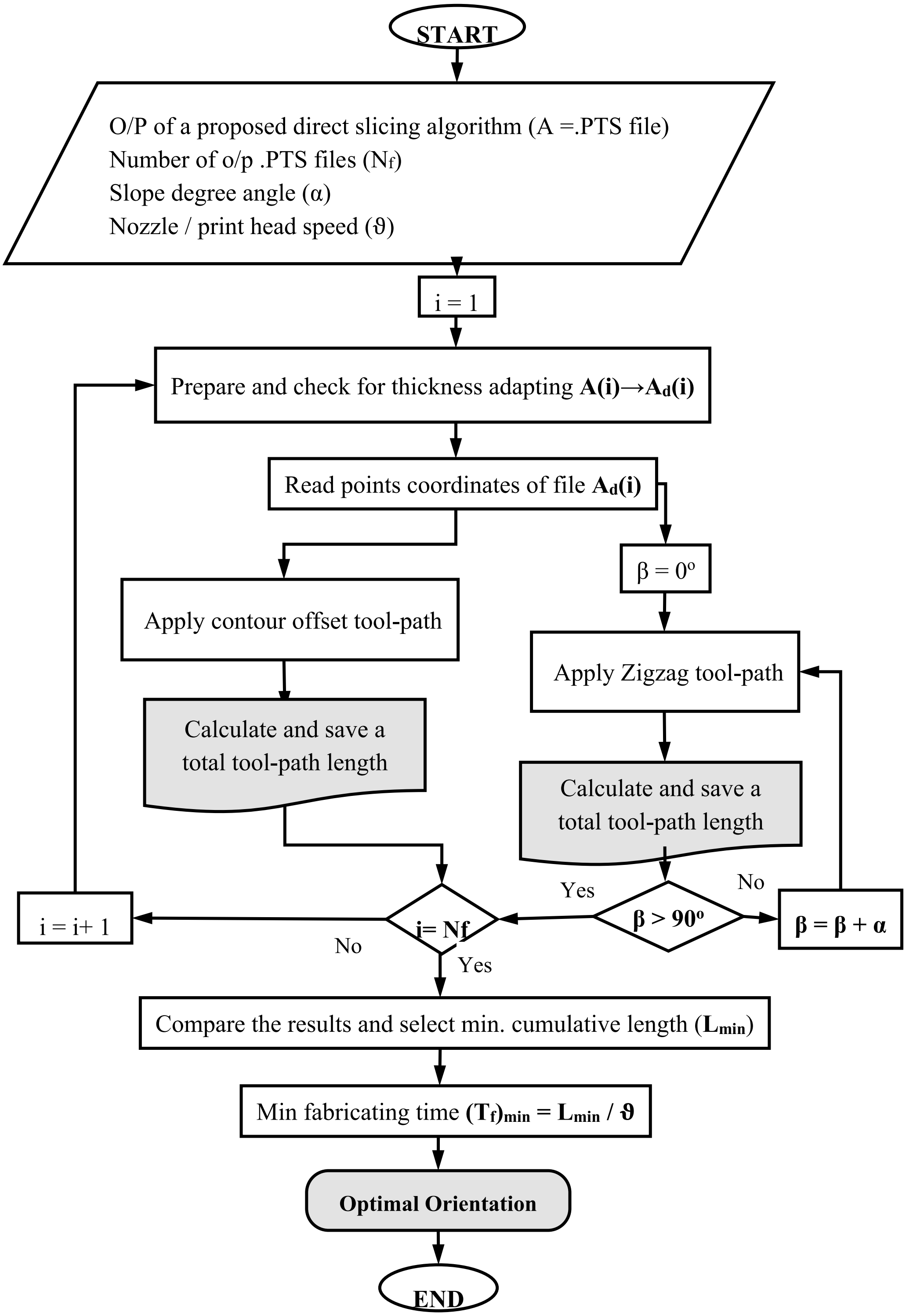


Fig. 15 Algorithm for determining the optimum orientation about the two axes based on the fabrication time

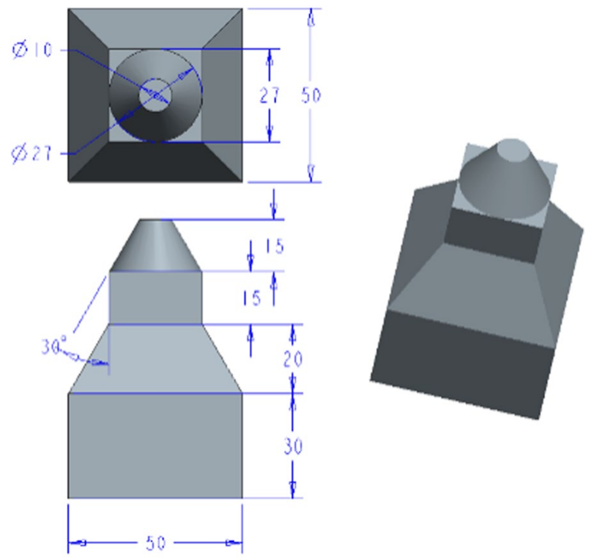


Fig. 16 Detailed drawing of original 3D CAD solid mode shows the CAD for a regular shape in solid modeling representation, designed using PTC Creo Parametric CAD software as case study no. 1

mentioned above, a series of recent approaches and strategies were designed and implemented. An algorithm was proposed to supply a unique means for improving the overall building efficiency. From the supported applications and the results, we obtain the following conclusions:

- The developed tool-path generation strategies (contour offset and zigzag line tool-path) can effectively balance the AM surface quality and fabrication efficiency requirements. Also, there is an adaptive stage for the sliced layers to enhance the surface quality and overall fabrication efficiency by reducing the build time using a percentage proportional to the CAD model's geometrical shape. In the case study, 47.3% of the build time was saved.
- A simple, complex CAD model was also used to validate the proposed algorithm, which justifies the accuracy and effectiveness of the algorithms. The mathematical models built can be used to minimize the build time to a minimum target.
- In this research, the AM users can benefit by saving the cost and time. The parts were fabricated with a high degree of accuracy, and the surface finish was suitable for determining the optimal process parameter.

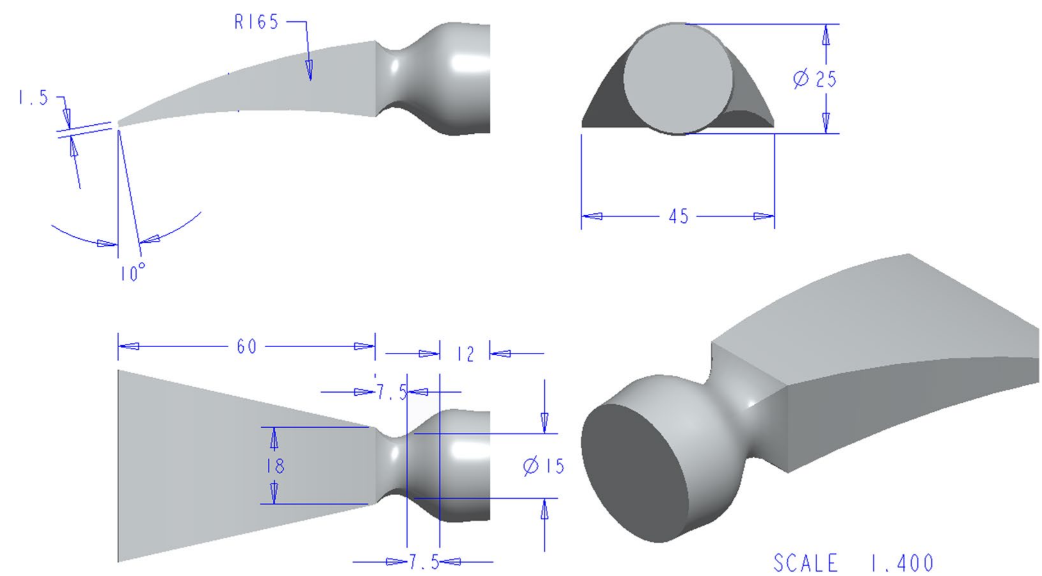


Fig. 17 Detailed drawing of original 3D CAD solid mode shows the CAD for a complex shape in solid modeling representation, designed using PTC Creo Parametric CAD software as case study no. 2

Table 1 Evaluation of building time criteria in the case study no.1

					$\theta_Y=0°$		$\theta_Y=30°$		$\theta_Y=60°$		$\theta_Y=90°$	
					Total no. of layers and building time							
					N (Lyr)	**T (h:m)**	**N (Lyr)**	**T (h:m)**	**N (Lyr)**	**T (h:m)**	**N (Lyr)**	**T (h:m)**
$\theta_X=0°$	Adaptive slicing	Zigzag tool-path	Slope angle	0°	100	3:00						
				30°		2:59						
				60°		2:58						
				90°		3:02						
		Contour offset				2:30						
	Uniform slicing	Zigzag tool-path	Slope angle	0°	160	5:41	168	5:29	131	5:31	100	5:39
				30°		5:40		5:29		5:32		5:40
				60°		5:40		5:28		5:31		5:39
				90°		5:41		5:29		5:31		5:38
		Contour offset				2:30		7:55		7:41		9:05
$\theta_X=30°$	Uniform slicing	Zigzag tool-path	Slope angle	0°	168	5:32	172	5:43	156	5:40	100	5:42
				30°		5:31		5:41		5:39		5:41
				60°		5:31		5:43		5:38		5:39
				90°		5:32		5:43		5:39		5:40
		Contour offset				2:22		7:10		6:20		7:14
$\theta_X=60°$	Uniform slicing	Zigzag tool-path	Slope angle	0°	131	5:28	150	5:38	143	5:39	100	5:40
				30°		5:29		5:38		5:38		5:40
				60°		5:30		5:39		5:42		5:40
				90°		5:29		5:38		5:40		5:39
		Contour offset				2:01		7:47		7:26		6:57
$\theta_X=90°$	Uniform slicing	Zigzag tool-path	Slope angle	0°	100	5:39	136	5:38	136	5:33	100	5:39
				30°		5:40		5:40		5:34		5:40
				60°		5:39		5:45		5:38		5:39
				90°		5:38		5:39		5:33		5:38
		Contour offset				2:12		9:16		10:18		10:18

Table 2 Evaluation of building time criteria in the case study no.2

					$\theta_Y = 0°$		$\theta_Y = 30°$		$\theta_Y = 60°$		$\theta_Y = 90°$	
					Total no. of layers and building time							
					N (Lyr)	T (h:m)	N (Lyr)	T (h:m)	N (Lyr)	T (h:m)	N (Lyr)	T (h:m)
$\theta_X = 0°$	Uniform slicing	Zigzag tool-path	Slope angle	0°	174	1:20	185	1:25	148	1:28	90	1:30
				30°		1:18		1:25		1:17		1:23
				60°		1:18		1:25		1:18		1:20
				90°		1:18		1:25		1:19		1:20
		Contour offset				2:30		2:33		3:10		3:29
$\theta_X = 30°$	Uniform slicing	Zigzag tool-path	Slope angle	0°	174	1:20	178	1:25	142	1:26	90	1:26
				30°		1:18		1:25		1:24		1:21
				60°		1:18		1:25		1:24		1:21
				90°		1:18		1:26		1:24		1:21
		Contour offset				2:22		2:10		3:09		3:04
$\theta_X = 60°$	Uniform slicing	Zigzag tool-path	Slope angle	0°	128	1:18	137	1:24	116	1:27	90	1:28
				30°		1:18		1:24		1:27		1:26
				60°		1:18		1:24		1:28		1:28
				90°		1:27		1:33		1:36		1:35
		Contour offset				2:01		2:19		3:43		2:46
$\theta_X = 90°$	Uniform slicing	Zigzag tool-path	Slope angle	0°	52	1:21	87	1:22	95	1:24	90	1:25
				30°		1:21		1:22		1:24		1:25
				60°		1:25		1:27		1:29		1:27
				90°		1:35		1:36		1:39		1:41
		Contour offset				2:12		2:39		3:48		3:29

Abbreviations
AM: Additive Manufacturing; CAD: Computer-Aided Design.

List of symbols
Ts: Post-processing time (min.); *L*: Total length of the tool-paths in all layers (mm); Lt: Total length of nozzle intervals (mm); Ltmax: Max. Layer thickness (mm); Ltmin: Min. Layer thickness (mm); *n*: Number of layers;; Np: No. of contour points; ofx: Contour offset in x-axis (mm); ofy: Contour offset in y-axis (mm); Rz,ϴ: Rotation matrix about z-axis; T: Total building time (min); Tc: Contour building time (min); Tf: Fabrication time (min); Tr: Internal building time(min); Tw: Intermediate time between layers (min); α: Slope angle (deg.); θx: Building orientation about x-axis (deg.); ϑxy: Nozzle speed at the layer plane (mm/min); θy: Building orientation about y-axis (deg.); ϑz: Nozzle speed at interval between layers (mm/min).

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Author contributions
MH conceived the idea, gives directives, suggested the algorithm method, and corrected the manuscript. AS carried out the design and the application. Both authors read and approved the final manuscript.

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References

1. Reichl K, Avci O, Inman D (2021) Temperature dependent damping in additively manufactured polymer structures. J Appl Comput Mech 7:993–1008
2. Sobhi A, Hamoud M, Barakat A (2019) Optimal building orientation based on minimum volumetric error using a new direct slicing algorithm. Int J Sci Eng Investing 8:43–48
3. Venkatesan US, Pande S (2017) Efficient process planning strategies for additive manufacturing. In: ASME 12th international manufacturing science and engineering conference collocated with the JSME/ASME 6th international conference on materials and processing, June 4–8, Los Angeles, California, USA, pp V002T01A008-V002T01A008
4. Singh R, Singh S (2017) Additive manufacturing: an overview. J Manuf Syst 38:118–130
5. Srivastava M, Maheshwari S, Kundra T, Rathee S (2017) Estimation of the effect of process parameters on build time and model material

volume for FDM process optimization by response surface methodology and Grey relational analysis. In: Wimpenny DI, Pandey PM, Kumar LJ (eds) Advances in 3D printing & additive manufacturing technologies. Springer, Singapore, pp 29–38
6. Huang Y, Leu MC, Mazumder J, Donmez A (2015) Additive manufacturing: current state, future potential, gaps and needs, and recommendations. J Manuf Sci Eng 137:014001
7. Yan X, Gu P (1996) A review of rapid prototyping technologies and systems. Comput Aid Des 28:307–318
8. Guo N, Leu MC (2013) Additive manufacturing: technology, applications and research needs. Front Mech Eng 8:215–243
9. Bi M, Xia L, Tran P, Li Z, Wan Q, Wang Li, Shen W, Ma G, Xie YM (2022) Continuous contourzigzag hybrid toolpath for large format additive manufacturing. Addit Manuf. https://doi.org/10.1016/j.addma.2022.102822
10. Natha P, Olsona JD, Mahadevana S, Lee Y-TT (2020) Optimization of fused filament fabrication process parameters under uncertainty to maximize part geometry accuracy. Addit Manuf 35:101331
11. Luo N, Wang Q (2016) Fast slicing orientation determining and optimizing algorithm for least volumetric error in rapid prototyping. Int J Adv Manuf Technol 83:1297–1313
12. Sasaki Y, Takezawa M, Kim S, Kawaharada H, Maekawa T (2017) Adaptive direct slicing of volumetric attribute data represented by trivariate b-spline functions. Int J Adv Manuf Technol 91:1791–1807
13. Hamoud M, El-Wahab AI, Barakat A (2008) A simple algorithm to orient and slice the CAD model for rebuilding using rapid prototyping. In: The international conference on mechanical design and production (MDP), pp 298–312
14. Das P, Mhapsekar K, Chowdhury S, Samant R, Anand S (2017) Selection of build orientation for optimal support structures and minimum part errors in additive manufacturing. Comput Aid Des Appl 14:1–13
15. Dani T, Kamdi P, Nalamwar G, Borse V (2013) Multi objective optimization of built orientation for rapid prototyping of connecting rod. Int J Sci Res Manag 1:13–18
16. Phatak AM, Pande SS (2012) Optimum part orientation in rapid prototyping using genetic algorithm. J Manuf Syst 31:395–402
17. Barányi I (2020) Characterization of tribological behavior of surface topographies by roughness measurement at the beginning of the wear process. Acta Tech Jaurinensis 13(2):151–160
18. Shi K, Cai C, Wu Z, Yong J (2020) Slicing and support structure generation for 3D printing directly on B-rep models. Vis Comput Ind Biomed Art 2:3. https://doi.org/10.1186/s42492-019-0013-x
19. Jung JY, Chee S, Sul IH (2021) Automatic segmentation and 3D printing of A-shaped manikins using a bounding box and body-feature points. Fash Text 8:13. https://doi.org/10.1186/s40691-021-00255-8
20. Han X, Zhan Z, Song X, Cui L (2022) An additive manufacturing direct slicing algorithm based on a STEP model. Electronics 11:1582. https://doi.org/10.3390/electronics11101582
21. Gomez G, Cortés C, Creus A, M.Z., Moreno, A. (2022) Generation of continuous hybrid zig-zag and contour paths for 3D printing. Int J Adv Manuf Technol 119:7025–7040. https://doi.org/10.1007/s00170-021-08418-z
22. Sabourin E, Houser SA, Bøhn JH (1996) Adaptive slicing using stepwise uniform refinement. Rapid Prototyping J 2(4):20–26

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