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ORIGINAL ARTICLE

A new approach to the design and optimisation of support structures in additive manufacturing

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Abstract Support structures are required in several additive manufacturing (AM) processes to sustain overhanging parts, in particular for the production of metal components. Supports are typically hollow or cellular structures to be removed after metallic AM, thus they represent a considerable waste in terms of material, energy and time employed for their construction and removal. This study presents a new approach to the design of support structures that optimise the part built orientation and the support cellular structure. This approach applies a new optimisation algorithm to use pure mathematical 3D implicit functions for the design and generation of the cellular support structures including graded supports. The implicit function approach for support structure design has been proved to be very versatile, as it allows geometries to be simply designed by pure mathematical expressions. This way, different cellular structures can be easily defined and optimised, in particular to have graded structures providing more robust support where the object's weight concentrate, and less support elsewhere. Evaluation of support optimisation for a complex shape geometry revealed that the new approach presented can achieve significant materials savings, thus increasing the sustainability and efficiency of metallic AM.

Keywords Additive manufacturing · Support structures optimisation · Selective laser melting · Cellular structures design

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1 Introduction

The additive manufacturing (AM) of parts through technologies such as selective laser melting (SLM) and electron beam melting requires the presence of external support structures because materials employed in those processes, typically metals (aluminium, steel, titanium, copper and nickel-based alloys), do not provide sufficient support for a overhanging object. Support structures are typically hollow or cellular structures that are sacrificed after the object's build, thus they represent a waste in the AM process. The fabrication of these sacrificial supports requires time, energy and material, as its supported functional object does. The amount of material wasted by fabricating support structures affects the manufacturing costs, especially when high-values metal alloys such as titanium are employed, for instance in the production of aerospace components. Furthermore, the presence of support structures increases both the time required for the part manufacturing and the time and complexity of post-manufacturing operations. In fact, support removal and surface polishing are usually carried out by expensive hand polishing. Minimising the amount of supported surfaces can shorten this operation, thus improving post-process efficiency. Consequently, design and optimise material-efficient support structures are highly demanded to improve the sustainability and efficiency of metallic AM.

In this paper, we introduce an alternative approach to the optimal design and generation of support structure in AM using SLM process as a typical case study. In order to minimise the amount of support required by the part built by SLM process, we implement a two-step optimisation algorithm. As first step, the best orientation to minimise the volume of support is located, among all the possible orientations; secondly, once the optimal orientation is identified, a second step optimisation performs a support microstructure optimisation in order to further reduce the support volume. In order to design of the microstructure topology for the supports, we employ 3D surfaces generated by pure mathematical expression. This approach presented high flexibility to design cellular structures with different densities, thus overtaking limitation presented by solid modelling software commercially available today.

1.1 Support structures

For a given object, one of the more effective ways to reduce the amount of support needed is to orientate the object into an optimal building position. Depending of the artefact built orientation, in fact, the amount of bottom surface that needs the supports change sensitively. A previous research [1] investigated the optimal orientation to minimise support structures for stereolithography process, an AM process for plastic parts. In this study, the support was simulated to identify where the part became unstable, overhangs appeared and components that were separated initially and connected later to the rest of the part. Also, the surface area of the support structure that was in contact with the object was minimised to improve the quality of the surface finish. When two different orientations of an object shows the same amount of support structure, the orientation with the lower centre of mass was chosen, since it was more stable. In this research work, supports do not present cellular structures; instead they were treated as solid blocks of materials. An effective way to significantly minimise the amount of material volume for supports could be a support design with an internal cellular structure. Support structures in fact have been typically designed as hollow or cellular structure to save materials and energy. A support design approach using cellular structures was presented in [9], where some airier support structures were designed, in order to overcome the disadvantages of supporting structures made of solid standing walls. In most of the support structure generation packages commercially available today, the supports' cellular structure design is implemented by combining a number of basic cell elements. For instance, the support generation software developed by a company named Materialise [6] locates and group close surfaces with same inclination and implements a list of rules to determine the appropriate type of supports, such as blocks for large surface areas, lines for narrow surfaces, points for very small features, gussets for overhanging parts and web support for circular areas [13]. Although this method presents the possibility for users to tailor the support topology by giving the possibility to choose among different cells type, few drawbacks need to be acknowledged. Very often, the operation of optimal support is initially approximated, and users need to refine it manually relying on their own experience. Also, unavoidably limits to the surface continuity at the junctions between struts and node fillets are introduced, when different cell types are in contact. This is a problem common to many solid modelling software applications, and it can lead to local concentration of stress that can degenerate into a structure collapse [3]. Furthermore, the eventual presence of sharp edges or cavities could facilitate the not uniform distribution of heat during the laser sintering process, therefore causing distortion. An additional drawback is also the impossibility to develop a regularly graded support structure, which could enhance to an optimal distribution of cellular structure density according to the object weight distribution. Clearly, an optimal distribution of support structures density that provides more robust support where the object weight concentrates, and reduced density elsewhere, would enhance the opportunity to achieve an optimal reduction of support volume.

1.2 Design of cellular support structures

There are several ways to design cellular structures; each method has its own advantages and disadvantages. Traditionally cellular structures were created using traditional commercial CAD packages. However, these packages have been proven to be unsuitable for potentially large complex micro-architectures due to vast number of Boolean operation needed [14]. Alternatively, voxel modelling presents a more straightforward way to perform Boolean operations. However, this method requires high resolution volumes to sufficient represent geometries using voxels.

A relatively simple image-based approach to the generation of cellular structures is presented in [12]. In this work, the bounding geometry, defined using a CAD model, is sliced into a number of binary images. Each slide is then treated with a Boolean operator to introduce a number of simple unit cells. This slice-based approach avoids the need of handling triangulated surfaces for the creation of a standard tessellation language (STL) file. However, this is likely limited to 3D printing where image-based slices may be used. As with any purely voxel-based method, it also results in a poorly defined geometry at the boundaries [5].

Another approach to the generation of micro-architectures is through the use of implicit functions. This approach has been employed in [3] and more recently in [7]. This approach uses a set of periodic implicit functions, such as the Schoen gyroid [10], to create microstructures. By introducing functional variations to the equations, it was possible to functionally grade the microstructure. However, there were no methods given to precisely control the grading, such as the minimum and maximum volume fractions. Furthermore, this method provides a compact representation of the complex structures, and through the use of an appropriate isosurfacing algorithm, a straightforward way to produce triangulated surfaces.

In this study, we adopt the implicit functions method to design cellular structure to act as support for AM platforms.

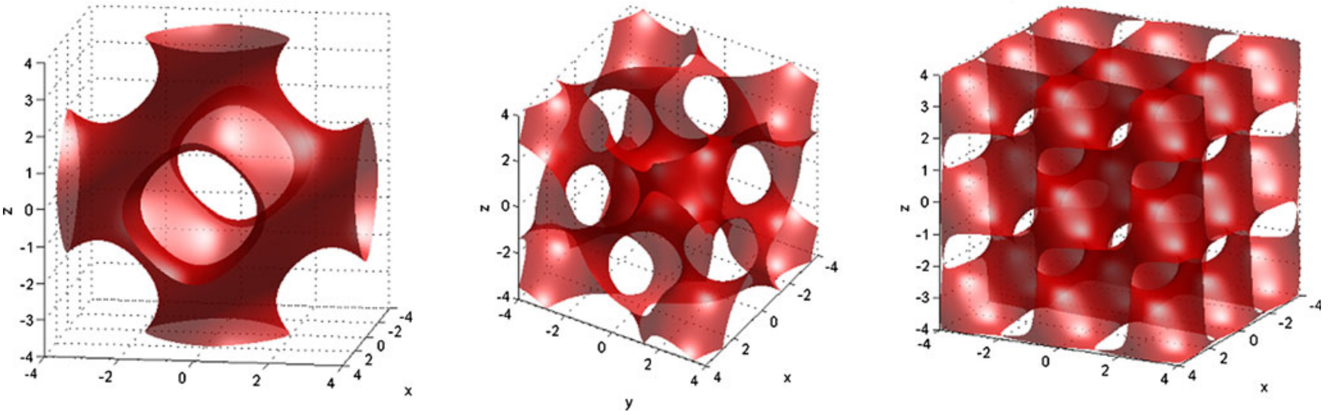

Fig. 1 From the left, representation of level surfaces expressed by Eqs. (1)–(3), respectively

The generation of 3D solid geometries is performed by implicit functions expressed in the form: $f(x, y, z)=0$, where $f = \Re^3\Re$.

Implicit functions provide flexible way to design complex cellular structures; also, they provide a compact representation for these structures.

The periodical surfaces that we present in this work are the “Schwartz” equations [11] and two others generated by the combination of trigonometric functions, known as “Gyroid”, and “Diamond” equations.

Schwartz level surface equation:

$$\cos(x) + \cos(y) + \cos(z) = 0 \tag{1}$$

Gyroid level surface equation:

$$\cos(x)\sin(y) + \cos(y)\sin(z) + \cos(z)\sin(x) = 0 \tag{2}$$

Diamond level surface equation:

$$\begin{aligned}\sin(x)\sin(y)\sin(z) &+ \sin(x)\cos(y)\cos(z)\\ &+ \cos(x)\sin(y)\cos(z)\\ &+ \cos(x)\cos(y)\sin(z) = 0\end{aligned} \tag{3}$$

The surfaces generated through 3D pure mathematical expressions are triangulated to generate a 3D solid structure; the mesh is then transferred into STL file formal specifications, in order the support to be processed by the rapid prototyping machine (Fig. 1).

2 Design of optimal support structures for additive manufacturing

2.1 Optimisation of part builds orientation

For a given object, the amount of support structures is directly determined by the build orientation. In fact, depending on the artefact built orientation, the amount of bottom surface that need supports change sensitively.

The following is described: the procedure that is designed to locate the best orientation to minimise the volume of support, among all the possible orientations, was developed. The optimisation is performed by an algorithm implemented in Matlab code. Following, the structure of the algorithm that executes the orientation optimisation, i.e. the first step of the total support structure optimisation, is schematically proposed, as it is shown in Fig. 2. The geometry of the object is defined by the STL used as the input file for the

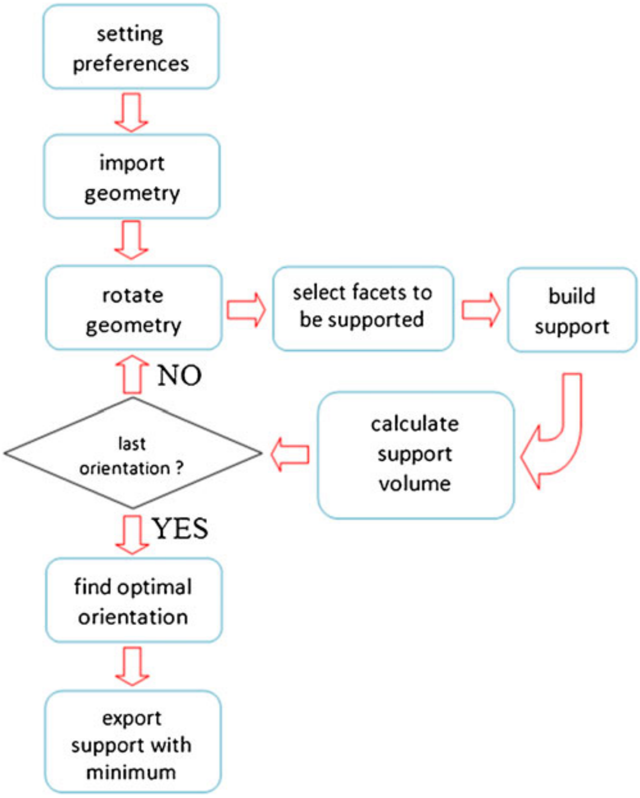

Fig. 2 Schematic of first step optimisation for optimal orientation to minimise support volume

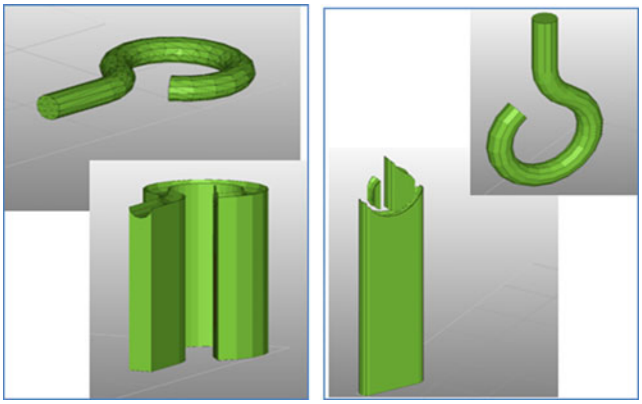

Fig. 3 Examples of solid supports generated for arbitrary orientations

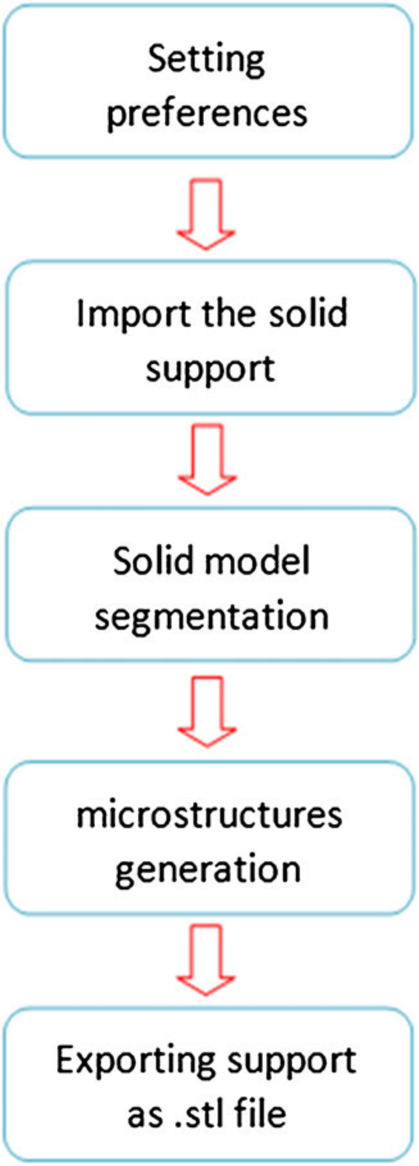

Fig. 4 Schematic of second step optimisation for generation of graded microstructure

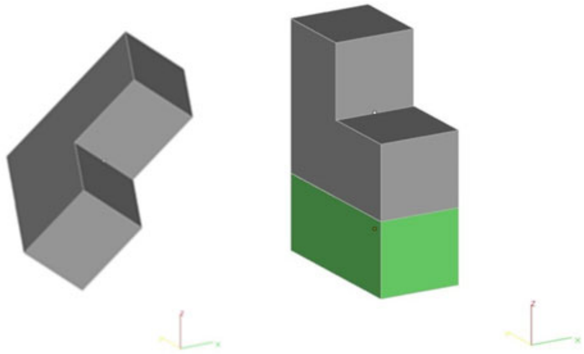

Fig. 5 "test.stl" Geometry in original (*left*) and optimal (*right*) orientations. In *green*, the associated solid support

optimisation system. The STL file, which provides a description of the surface geometry in $\Re^3$, is imported into the Matlab environment.

The initial step presents the possibility for users to choose (1) the distance "z_base" between the platform base and the lowest point on the bottom surface of the part and (2) the parameter "slop_deg", threshold angle of inclination with respect to the platform bed that is used to select the bottom surfaces that are to be supported. Surfaces that are sloped less than the threshold are considered to need support. On the next step, the input geometry is imported, either in the form of ASCII or binary STL file. For each possible generation, the geometry is then rotated around x- and y-axes, with default resolution of 5°. Higher resolutions can be easily specified by the user; however, this would increase the number of possible orientations (theoretically infinite resolution) and consequently the algorithm iterations and the total computational time required by the optimisation. Once the 3D object geometry is acquired in the STL format, as known, the solid rotation is performed by multiplying the transpose of the matrix V containing the vertices coordinates of the object mesh, by rotation matrices around the X- and Y-axes [4]. V_r matrix of vertices describing the rotated object is calculated as in Eq. (4):

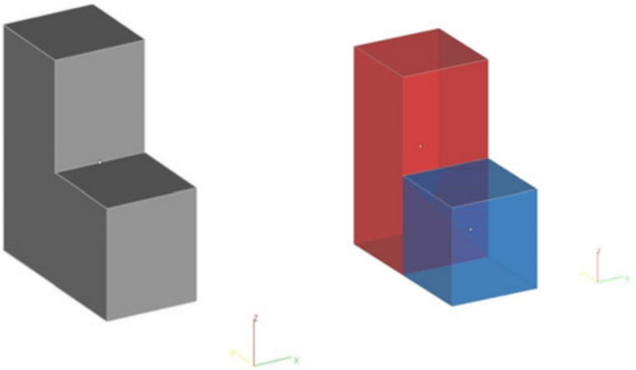

Fig. 6 Segmentation of entire volume of the object into sub-volumes

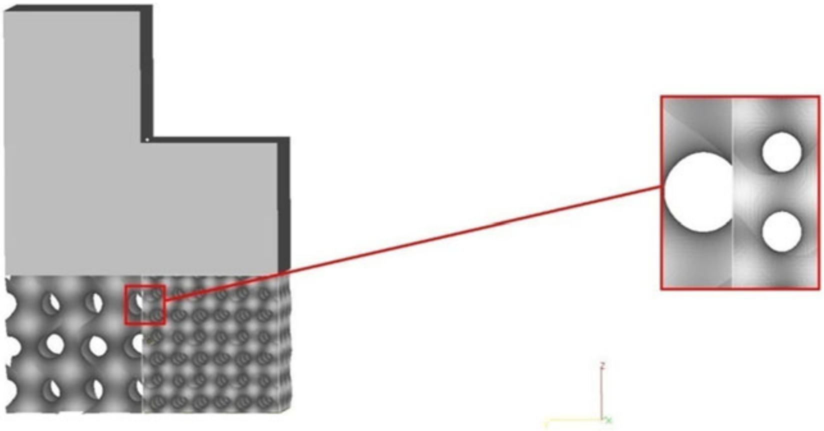

Fig. 7 Discontinuities might appear at the interface between block with different cell size

$$V_r = R_y \cdot R_x \cdot V^T = \begin{bmatrix} \cos(\vartheta_{\mathrm{y}}) & 0 & \sin(\vartheta_{\mathrm{y}}) \\ 0 & 1 & 0 \\ -\sin(\vartheta_{\mathrm{x}}) & 0 & \cos(\vartheta_{\mathrm{x}}) \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\vartheta_{\mathrm{x}}) & -\sin(\vartheta_{\mathrm{x}}) \\ 0 & \sin(\vartheta_{\mathrm{x}}) & \cos(\vartheta_{\mathrm{x}}) \end{bmatrix} \cdot V^T \tag{4}$$

For each rotated geometry, the facets that need to be supported are selected, in accord with the inclination angle specified initially by a threshold value slop_deg in the preferences.

The support is built for the selected surfaces, and the relative support's volume is calculated and stored. Figure 3 shows some examples of the solid supports generated for "hook.stl" geometry file, at arbitrary chosen orientations, with the threshold value slop_deg set at *85°*. The threshold value of 85° has been chosen arbitrarily, in order the support structure (green colour in Fig. 3) to be emphasised.

The algorithm iteration loop is on until the supports for all the orientations are calculated. Once all the possible orientations are investigated, the orientation that requires minimum support volume is identified, and the relative support volume exported in the form of STL file for eventual visualisation/manipulation.

2.2 Design of supports structures through 3D mathematical functions

A second algorithm described in this paragraph is used for the design of optimal cellular structures, to act as support for AM platforms. The proposed method provides a function to tailor the volume fraction of the support structure to generate more robust support to where needed; thus, it enhances for efficient employment of support structures. Following in Fig. 4, the structure of the algorithm to design-graded support structures is schematically proposed.

The algorithm first starts by importing the STL geometry oriented optimally, as the result of the first stage optimisation. For the example purposes, we illustrate each algorithm step on a simple 3D geometry file, "test.stl".

Figure 5 shows the test.stl geometry in the original orientation (left), and the optimal orientation (right) that minimise the volume of support. For illustration purposes, a choice to fully support all the downward oriented surfaces has been done, by setting the threshold "slop_deg=90°". Also, in the preference settings, a distance from the platform

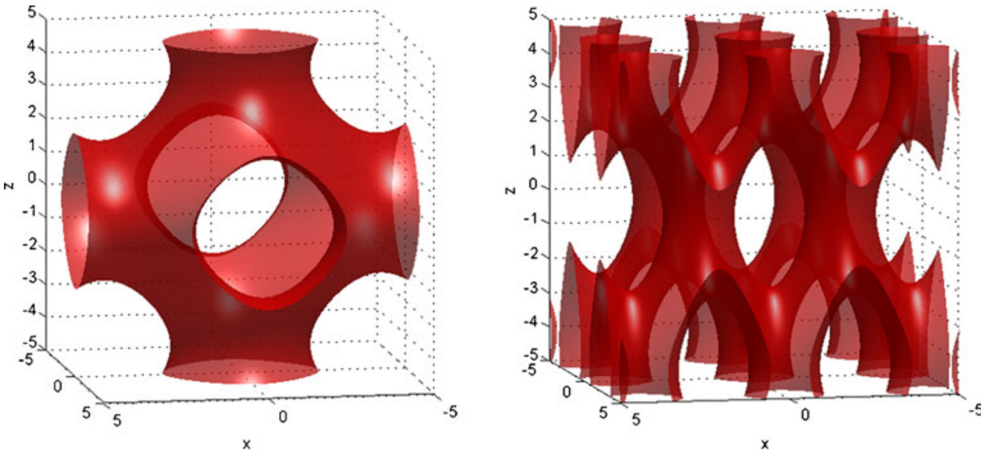

Fig. 8 Schwartz cells with same periodicity in z direction ($k_{z1}=k_{z2}$)

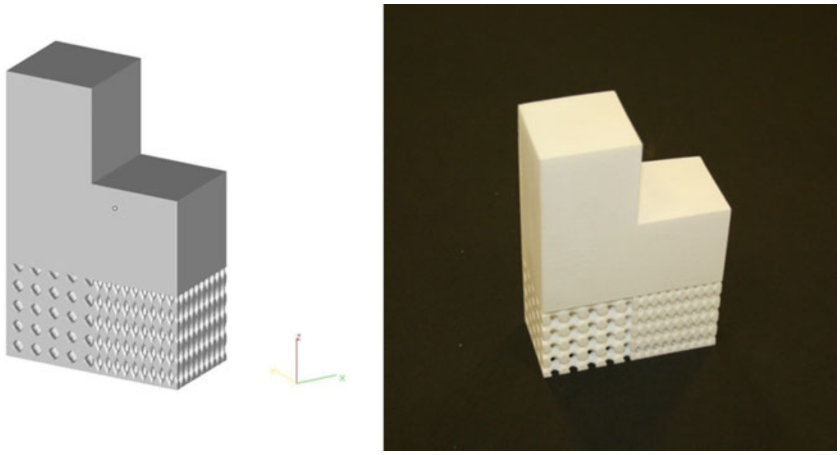

Fig. 9 Final support structure for test.stl geometry (*left*) and manufactured geometry (*right*)

base of the machine has been set to *2 cm*, in order to increase the height of support necessary. The choice of slop_deg and z_base has been done for the purpose of illustrative example. The optimally oriented test.stl geometry and the associated solid support are visible in Fig. 5.

Once the test.stl has been imported, the solid volume is segmented; in Fig. 6, two sub-volumes blocks have been identified, as represented in different colours. For each block, an associated microstructure support is generated through the use of implicit functions, and using cells with different volume fraction. The use of implicit functions in fact allows to specify the volume fraction by simply introducing a variation to the original equations. One possibility is changing the periodicity of the trigonometric terms of the equation, by adding a term *k*. Adding a term *k* is an effective way to change cell periodicity, and it can be employed as method to change the volume fraction of cellular structures. For illustration purposes, we modify the expression of the Schwartz equation as in Eq. (5); however, the cell periodicity of cellular structures defined by other implicit functions can be modified in the same way.

$$\cos(k_x \cdot x) + \cos(k_y \cdot y) + \cos(k_z \cdot z) = 0 \qquad (5)$$

It is important to acknowledge that, as changing the cell periodicity will generally affect the cell size, this typically causes that the continuity of the implicit trigonometric function is generally not conserved after having merged the support with different cells size, as clearly observable in Fig. 7. The detail of the support microstructure (in the figure, the red square at the right) highlights a typical discontinuity that can appear at the interface between block with different cell sizes.

However, from the structural point of view, the formation of discontinuities is not expected to represent a serious issue in the specific application of support structures. When a discontinuity appears, since each sub-volume of the object displaces a vertical load which is vertically sustained by the corresponding support block below, there are no transverse load conditions that could yield to stress concentrations such that to degenerate into a structure collapse. In fact, the use of minimal surfaces allows the stress to distribute into the structure homogeneously, due to the absence of cavities or peaks that would locally concentrate the stress otherwise [3]; thus, they present good potentialities to act as support.

In order to limit the number of discontinuities at interfaces between blocks of different cell types, the periodicity along one or more directions can be conserved. For instance, the two different Schwartz cells represented in Fig. 8 have been produced assuming the same periodicity along the *z* direction, fixed at k_{z1}=k_{z2}=0.75, and using the values k_{x1}= 0.75, k_{x2}=1.5, and k_{y1}=0.75, k_{y2}=1.5 for the *x*-, and *y*-axis, respectively.

Figure 9 shows the final support cellular structure for the "Test.stl" part, in its optimal orientation. As noticeable, the support presents a graded volume fraction, given by the combination of the different periodic microstructures; in order to limit surface discontinuities, the periodicity on *z* direction has been conserved, by specifying k_{z1}=k_{z2}. The manufactured artefact and its support are shown in Fig. 9. In order to turn the surface model in Fig. 8 into final support structure in Fig. 9,

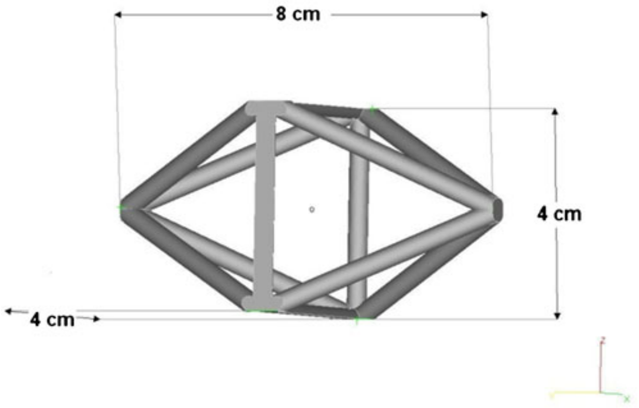

Fig. 10 Truss structure geometry "cell.stl"

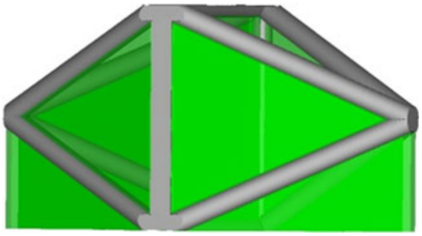

Fig. 11 Solid support for original orientation

the 3D surface is first tessellated, therefore mapped into 3D triangular mesh model; secondly the 3D mesh is exported as ASCII. STL file, so that it is can be processed by any additive manufacturing machine. Figure 9 shows the artefact manufactured, for prototyping purpose, by an EOSINT P 800 Selective Laser Sintering Machine (EOS GmbH 2011).

The STL file containing the support for the entire part is finally exported for eventual visualisation/manipulation. The diagram in Fig. 4 summarises the algorithm routines discussed.

3 Evaluation of a complex shape structure as a case study

A more complex shape geometry showed in Fig. 10 is used as a second case study to evaluate new support structure design and optimisation algorithm. The geometry “cell.stl” represents a cylindrical trusses cell core, typically employed for the production of lightweight aerospace applications. The limits of conventional manufacturing processes for the manufacturing of truss structures have been previously discussed; in this context, it is briefly stated that in manufacturing a complex geometry such as the cell.stl, one would be typically impossible without welding the single trusses, and the welding would produce weak junctions where cracks and corrosion could be facilitated.

In the parameters set for the optimisation, it has been set to support all the downward surfaces inclined less than *35°*, in accord with the actual standards on EOS M270 machine (EOS GmbH 2011). The height between the platform base and the part has been set to zero. The support microstructure has been generated using the Schwartz equation. The solid support for the original orientation generated by the algorithm is shown in green in Fig. 11; the support affects large portion of the object surface because in the original orientation almost all the trusses are horizontal or inclined less than 35°. In Fig. 12, the best orientation (with minimal amount of support needed) is shown at the left, and, for the purpose of comparison, the worst orientation (with maximum amount of support needed) is shown at the right, respectively.

The final support structure generated for the cell.stl is shown in Fig. 13; unlike for the test.slt case study, the support does not have a graded microstructure. This is because of the part symmetry that makes the weight to distribute with equal intensity on each of the supported trusses.

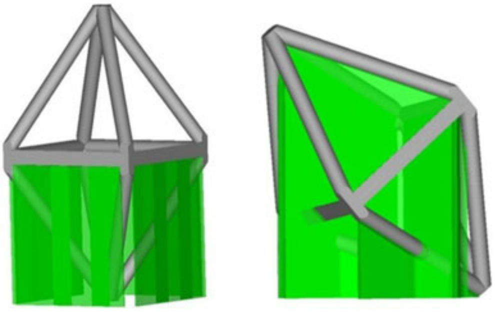

Fig. 12 Best (*left*) and worst (*right*) building orientation for cell.stl geometry

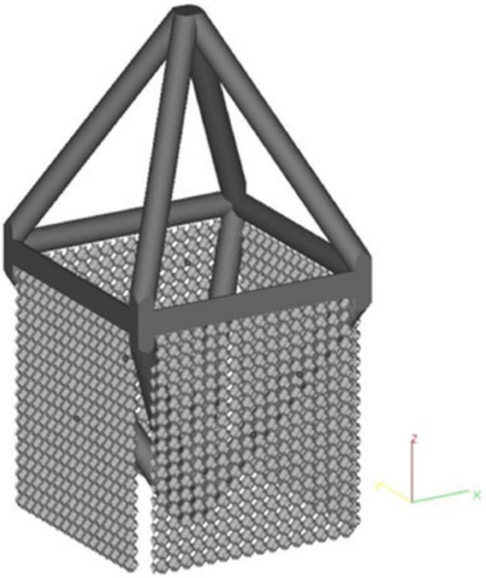

Fig. 13 Final support structure for cell.stl geometry

Table 1 Comparison of material saving for different built orientations

Built orientation	Volume of support (mm^3)	Material saving[a]
Original (θ_x=0°; θ_y=0°)	142.795	–
Best (θ_x=0°; θ_y=90°)	81.059	+43 %
Worst (θ_x=50°; θ_y=10°)	172.723	−21 %

[a] In respect to the original orientation

4 Result and discussion on support structures for a complex structure

The solid support for the original orientation (Fig. 11) affects large portion of the object surface because in such orientation almost all the trusses are horizontal or inclined at less than 35° with respect to the platform bed; thus, they considered requiring support. As consequence of building the geometry with this orientation, large portion of the object surface will be deteriorated because of their contact with the support, and expensive and long-time operations of surface finishing will be required during post-manufacturing stage [2, 8]. Furthermore, the volume of support will require the sintering of large amount of material powder, which has extra costs in itself, and also will increase time and energy for manufacturing process. Furthermore, due to the complex shape of the geometry, the operations of support removal could be difficult, especially without running into a risk of damaging any trusses. Table 1 shows a comparison of material savings for different built orientations; the best orientation shown at the left of Fig. 12 allows to a 45 % saving of support with respect to the original orientation, and to a 55 % saving with respect to the worst orientation. In the optimal orientation, most of the part volume is displaced in a way to support itself; only four trusses need external support structure—this enhances to an easier support removal and also minimises the amount bottom surfaces deteriorated by the contact with the support.

The implicit functions approach for the design of periodical microstructure allowed to easily specify the support structure for the optimally oriented part (Fig. 13). The topology described by the Schwartz equation enhanced a further 50 % material saving with respect to the full dense support shown in Fig. 12 (left). Furthermore, the use of trigonometric functions for the definition of cellular structures might facilitate the stress to distribute into the structure homogeneously, due to the absence of cavities or peaks that would locally concentrate the stress otherwise, thus avoiding support structure collapse.

5 Conclusions

This study has presented a new approach to the design and optimisation of support structures in additive manufacturing platforms such as SLM. This optimisation provides functions to minimising support structures through both the definition of an optimal part built orientation and the definition of optimally graded cellular structures. A Matlab algorithm that performs a two-step optimisation has been developed; firstly, the part orientation that requires the minimum support has been located among all the possible orientations; secondly, the cellular support structures for the optimal orientation is generated, through pure mathematical 3D implicit functions. The implicit function approach for cellular support design is found to be very versatile because it allows geometries to be simply defined by mathematical expressions. Optimisation evaluation results on a truss part with complex shape geometry demonstrated that significant materials saving, for instance up to 45 % for this case, can be achieved by an optimal part positioning, and further reductions can be obtained by designing cellular structures defined by implicit mathematical functions. This newly developed design and optimisation approach of cellular support structures exhibit great potential to achieve higher efficiency of the SLM process and consequently deliver time, material and energy savings.

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