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ADDITIVE MANUFACTURING WITH MODULAR SUPPORT STRUCTURES

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Abstract

Additive manufacturing is praised to have low material waste compared to conventional subtractive manufacturing methods. This is not always the case when the computer aided design (CAD) model consists of large overhangs. In such cases, fabrication of support structures are required to fill the space between the CAD model and the manufacturing bed. In post processing, these support structures must be removed from the model. These supports become waste and reduce the buy-to-fly ratio. In this paper, we present a pre-fabricated reusable modular support structure system which minimizes the fabrication of conventional support structures. The conventional supports are replaced with modular support blocks wherever possible. The blocks are stacked under the overhang with a robot arm until the overhang of the model is reached. Conventional supports can be fabricated on top when needed with fused filament fabrication. This strategy reduces fabrication of conventional supports. Thus, faster fabrication times are obtained with higher buy-to-fly ratios.

Keywords: Support structures, Modular, Additive Manufacturing, Robotic

1. Introduction

Additive manufacturing (AM) is a process where the computer aided design (CAD) model is manufactured additively layer by layer [1]. The CAD models designed in various CAD formats can be used by the triangulation into a Stereolithography (STL) file [2]. This triangulated mesh is sliced layer by layer to obtain the toolpaths which will be given to the machine for the construction of the physical model. During the construction of the CAD model, it might be necessary to build support structures to support overhanging parts of the model. These support structures, must be fabricated simultaneously with the model, and hence must be accounted for in the toolpath planning [3].

The introduction of the support structures increases the overall manufacturing time of the given CAD model. In addition to time, the material cost of the supports needed to create each part must also be taken into account [4]. These supports will become waste and reduce the buy-to-fly ratio of the given AM process. Since support structures are not part of the final geometry to be created, they need to be removed; a process that requires a significant amount of extra time and effort. Thus, it is in the industries best interest to reduce the amount of support structures required.

Several AM methods have been developed to minimize the use of support structures. Some methods try to determine the best orientation for manufacturing with respect to the primary build axis [5]. Others use multiple build axes [6], [7]. Some try to facilitate the easy removal of the support structures [8]. Some have partitioned models into smaller parts which can be fabricated separately to be assembled later [9]. Others use a secondary material for the support. The use of secondary support materials which are either weaker, soluble in a liquid solution, or melt at a lower temperature than the build material was a significant improvement in simplifying the removal of supports. To do this, the extrusion-based equipment should have a second extruder. The secondary material can be extruded in parallel with the current layer of build material [4].

This paper proposes a method for fused filament fabrication (FFF) which reduces the fabrication of the conventional support structures by replacing them with pre-fabricated reusable modular support blocks wherever feasible. With the aid of a robotic arm, the blocks are stacked under the overhanging portions of the CAD model until the desired build height is reached. The bulk of the support will be covered with the blocks and the remaining portion can be filled by fabricating conventional supports on top of the stacked support blocks. This strategy reduces the overall fabrication of conventional supports. Thus, faster fabrication times are obtained with higher buy-to-fly ratios.

In the next section, the paper starts by explaining the conventional support generation process for the overhanging areas. Section 3 then uses the newly developed modular support structures method to replace the conventional supports wherever possible. Section 4 provides the robot integration for placement of the modular support structures. Section 5 gives examines results with example models: Stanford bunny and the Atatürk portrait. Finally, Section 6 ends the paper with the conclusion of the work.

2. Conventional support generation

Given the STL file, the overhanging faces of the model that require support structures must be detected. These are found by checking the angle of each facet of the model which is lower than the minimum self-supporting angle from the horizontal XY plane. Such overhanging faces are visualized in Figure 1.

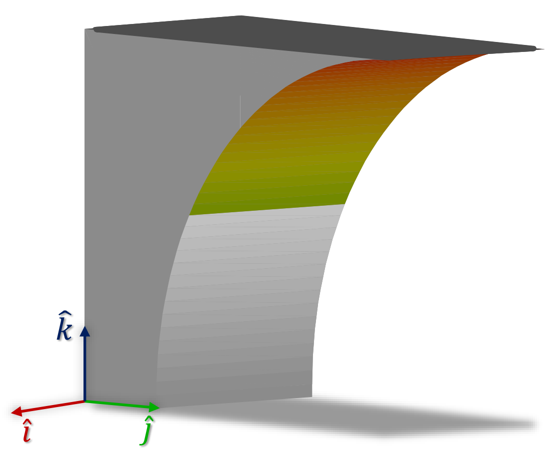

Figure 1. Overhanging faces that require support colored from green to red. Grey faces do not require support.

Using the vertices v_1, v_2 and v_3 from the STL model, surface normal $\vec{N}$ for each facet is calculated by taking the vector cross product of two edges of that triangle

$$\vec{N} = \frac{v_{12} \times v_{23}}{\|v_{12}\| \|v_{23}\|} \tag{1}$$

The Angle from the XY plane is calculated by using cosine law

$$\theta = \cos^{-1} \frac{\vec{N} \cdot -\hat{k}}{\|\vec{N}\| \|-\hat{k}\|} \tag{2}$$

The angle θ is calculated for each facet. The minimum self-supporting angle θ usually ranges from 30 to 60 degrees depending on the AM process and its parameters. Figure 2(a) shows the areas requiring support on the Stanford bunny. Facets where θ is lower than the minimum self-supporting angle are isolated from the rest of the model. In this list of facets, checking for the edges which are used only once gives us the boundaries of the area that requires supporting structures.

After the areas which require support are found, the supports need to be generated. This is done by first sampling the area. First minimum axis-aligned bounding box (AABB) of the model is found. The edges of the bounding box are used to generate two sets of planes with equidistant spacing. These planes face the direction of $\hat{\imath}$ and $\hat{\jmath}$ unit vectors and are perpendicular to the manufacturing bed. The equidistant spacing is determined by the size of the desired support structures inputted by the user. The support points are found by first intersecting the boundaries with $\hat{\imath}$ planes. The intersection is solved by triangle-plane intersection. This results in line segments lying on the $\hat{\imath}$ planes. Then, intersection of these line segments with the $\hat{\jmath}$ planes give the support points. These are the points which cannot be manufactured without extruding material under it. This space can either reach the manufacturing bed or lie on the model itself.

At each support point a ray is cast in the -$\hat{k}$ direction using Möller–Trumbore ray casting algorithm [10]. If the ray hits a facet, the support starts on the model. Otherwise the support starts from the manufacturing bed. Rectangular support structures are generated using the selected support width and the length from either the model or the manufacturing bed to the support point. These support structures are plotted in green in Figure 2(b).

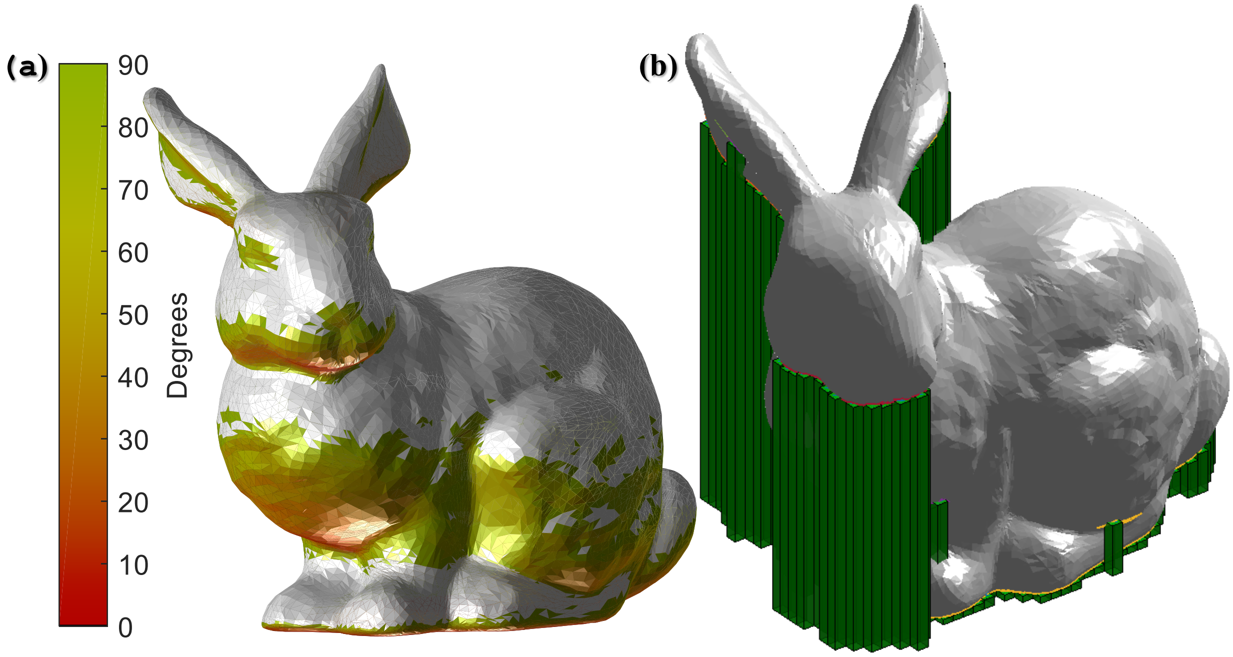

Figure 2. Analyzing the Stanford bunny for support structures: **(a)** Angle of facets less than 90 degrees **(d)** Conventional support structures generated for each support point

Support structures that start from the manufacturing bed are appropriate candidates for replacement with modular support structures. Placing the pre-manufactured modular support blocks reduces the deposition of the conventional support structures and thus improves manufacturing time while reducing the material costs. The next section gives the method to replace the conventional supports with the newly developed modular support structures.

3. Modular support structure generation

For reduction in cost and time, it is desirable to replace the conventional support structure with modular support structures. To start, one needs to determine which support structures can be replaced by the modular support blocks. The process starts by dividing the supports into levels in the $\hat{k}$ orientation. The height at which the supports are split is determined by the modular block size. Support structures divided into levels are given in Figure 3. Supports which lie on the model are not considered for replacement with the modular block placement, since a flat surface is required to place the modular blocks.

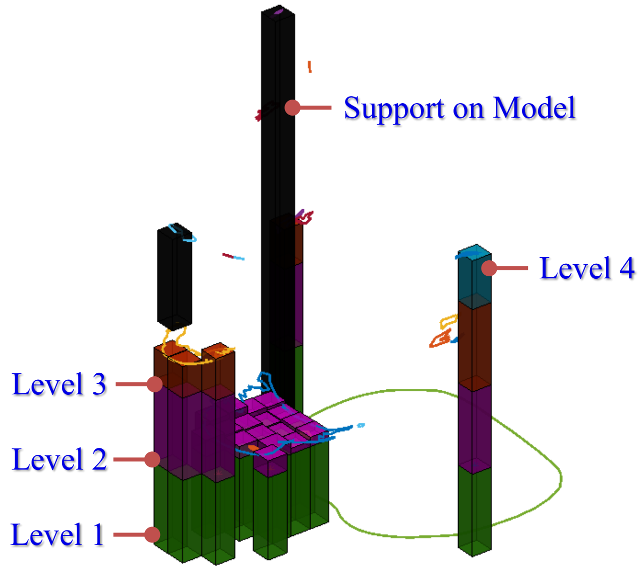

Figure 3. Conventional support structures split into levels with the given modular block height for the Atatürk model. The boundaries show the areas which require support.

For each support structure level, a two-dimensional support map is generated. The map contains the normalized locations of the support structures within the AABB. Each pixel on the map is in the size of one support structure. The map has the value of true for each $<\hat{\imath},\hat{\jmath}>$ coordinate pair containing support and false for the rest of the coordinates. A sliding window search is implemented on the map to find the optimum place for the modular blocks. This process is shown in Figure 4. The window has the size of a single modular support block. The window first moves in $\hat{\imath}$ direction. When the edge is reached, $\hat{\jmath}$ is incremented and $\hat{\imath}$ is swept again until every coordinate pair is searched. At each point, the number of support points covered by the block are recorded. The first block is placed where the maximum number of support points are covered. Then the process is repeated until all the points are covered.

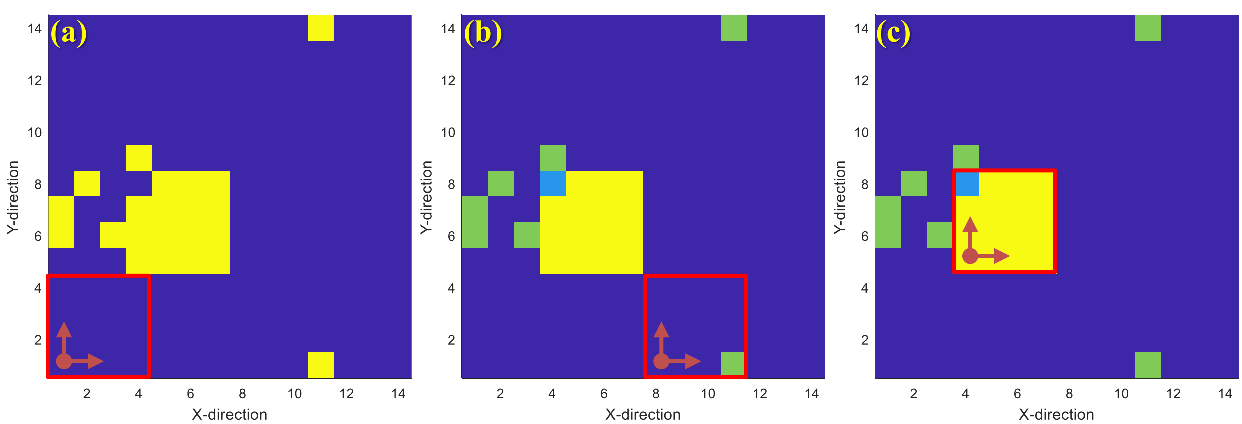

Figure 4. Sliding window search for placement of the modular block: **(a)** Windows is at the origin **(b)** Window has moved in the x direction **(c)** Window has found the maximum location

At the same time the support map is being swept, two other maps are checked. The first map is for the collision with the model and the second map is for collision with previously placed blocks. The model map is given in Figure 5(b) while the block maps are given in Figure 5(c). With these checks, blocks are only placed at feasible locations. A given point on the map may cover more support points, but it will not be selected if there is collision. After each placement of the block, the covered support points are removed. At the end of the process, if any support point is left which can not be replaced with modular support structures, it is saved for fabrication of conventional support structures. The remaining support points for the Atatürk model are shown in Figure 5(d).

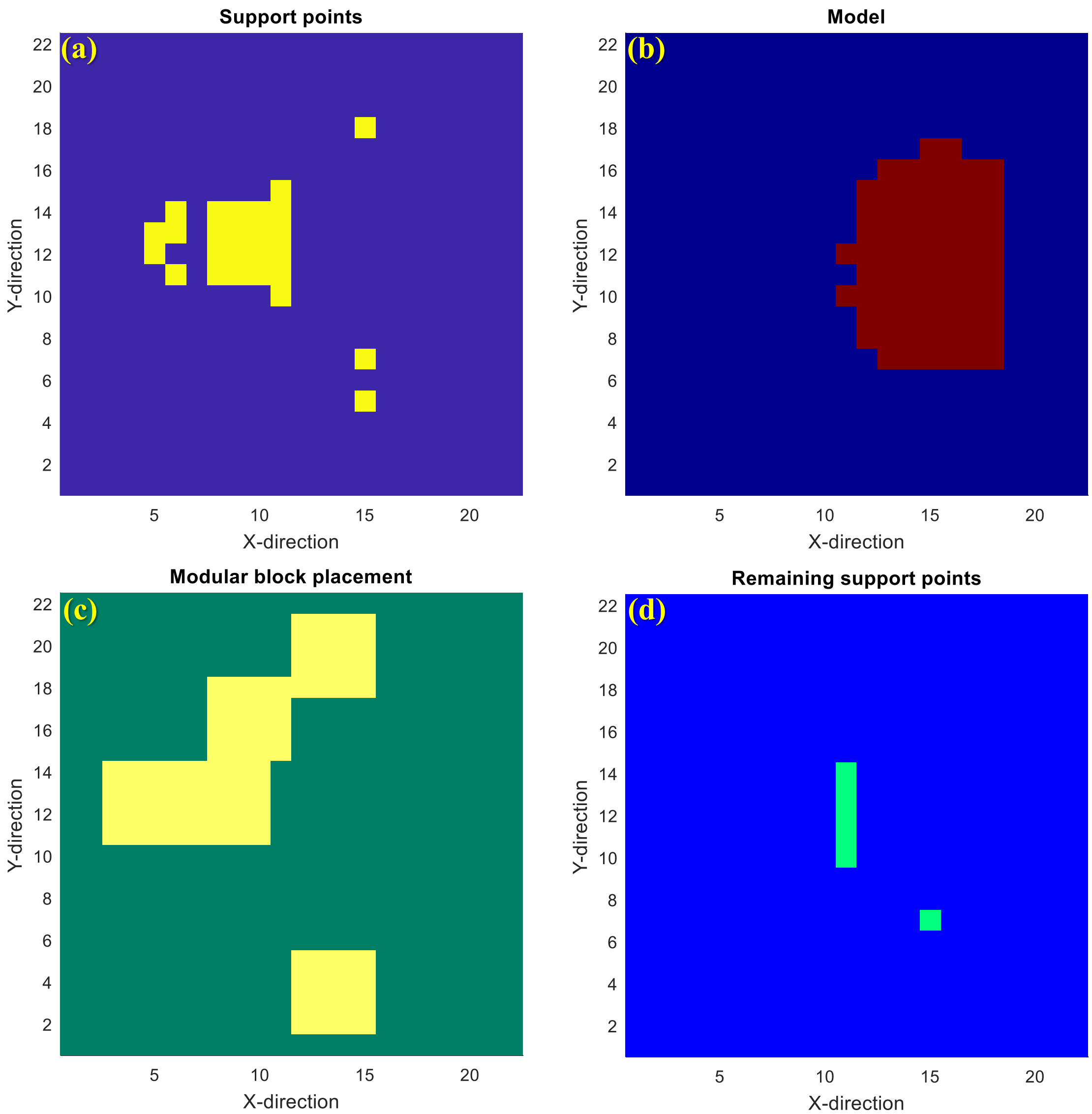

Figure 5. Block placement with consideration of collision with the CAD model: **(a)** Conventional support structure map **(b)** CAD model map **(c)** Modular block placement map **(d)** Remaining support points map.

For successful implementation of the proposed modular support structure concept, the design of the modular blocks is critical. The blocks should be placed with precision and should not be disturbed during the AM process. Thus, an interlocking system which limits the movement of the blocks are desired. This can be achieved by using magnetic aligners or mechanical interlocking structures such as that found in the Lego blocks. The next section uses the modular support structure data to formulate the modular support placement strategy with a robotic manipulator.

4. Robotic placement of the modular support structures

The proposed method uses robotic manipulator to place the modular blocks. The block placement for the given models is shown in Figure 6. and the manufacturing setup is given in Figure 7. The blocks are initially stacked on the left-hand side on the stack platform given in cyan. The robot can have a tool changer where two different tools are employed. The tools and the tool changer have not been shown in this work. The first tool is a suction cup tool which picks the blocks from the stack and places them at the desired locations. The second tool is an extruder which manufactures the layers of the model and the conventional support structures. The manufacturing bed is given in green, placed in front of the robotic manipulator.

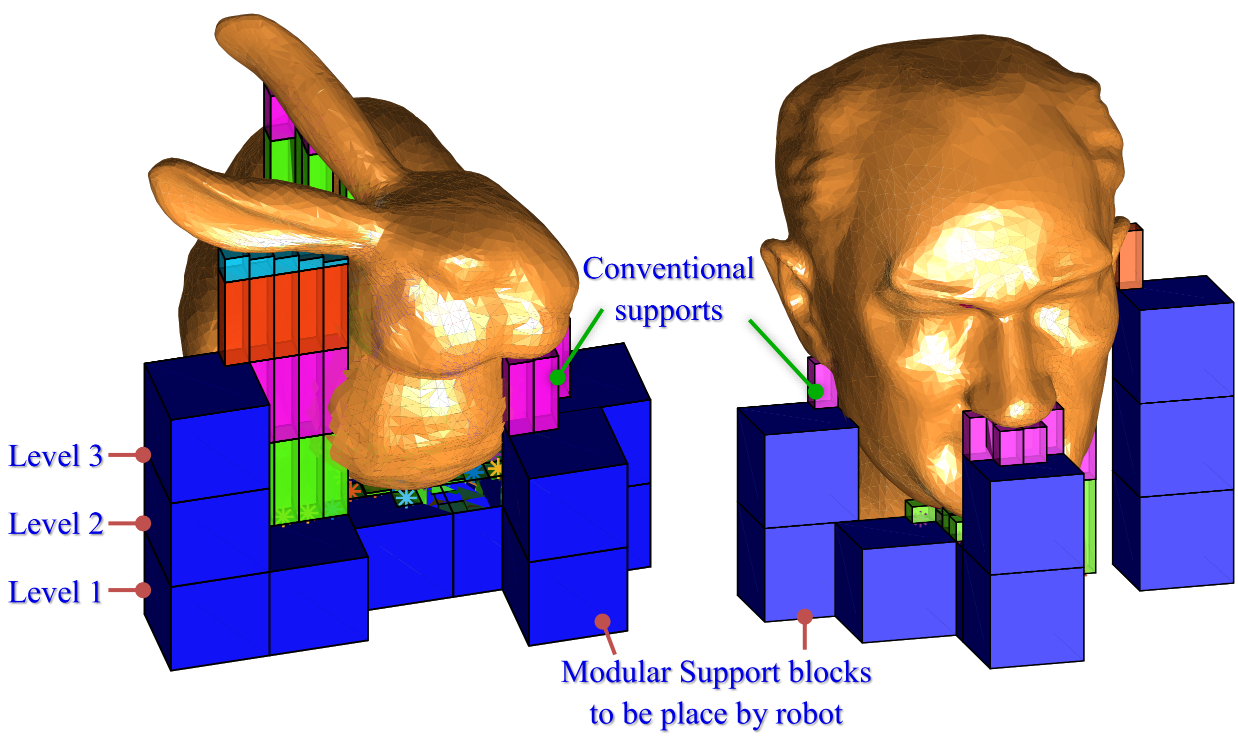

Figure 6. Modular support structures results: **(a)** The Stanford bunny **(b)** The Atatürk portrait

The process starts with the extrusion tool depositing the first layers of the model. When the level of the first modular support block is reached, the extrusion process stops. The robot changes the tool to the suction cup tool. This tool is used to pick and place the first level of blocks. After the blocks are placed, the tool is changed back to the extruder. The extrusion continues starting from this level and the process is repeated until all the layers are fabricated. Depending on the overhanging surfaces, new layers are deposited on some of the placed blocks and others are used as a base for new block placement. Given the initial position of the block on the stack, and the desired target position on the manufacturing bed, the joint interpolated trajectories for the 6DOF robotic manipulator are generated by using robot toolbox [11]. These trajectories are plotted in red in Figure 7.

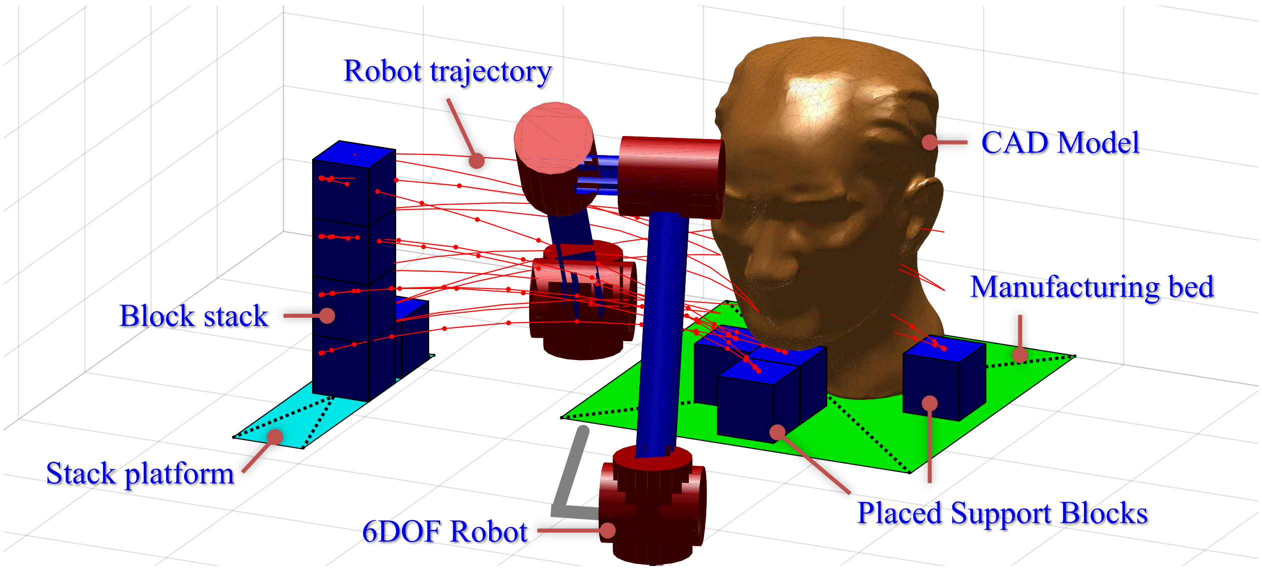

Figure 7. Robotic additive manufacturing setup with modular support block placement

With the introduction of the blocks, the material waste is reduced, and the fabrication time is improved. The next section gives the results for the proposed method.

5. Results and discussions

The algorithms were implemented on MATLAB© environment installed on a computer with Intel© I7 CPU, 8 GB of RAM. Using Modular support block dimensions of $40 \times 40 \times 40$ $[mm]$ with support spacing of 10×10 $[mm]$. The percent of volumetric improvement in the support structures are calculated and given in the table below.

Table 1. Comparison of the proposed method with the conventional method

Model	Facets	Vertices	Dimensions	Conventional	Proposed	Improvement
Atatürk portrait	*15270*	*7637*	*181x154x226[mm]*	*26.3[cm³]*	*8.4[cm³]*	*68%*
Stanford bunny	*33398*	*16701*	*229x177x226[mm]*	*46.5[cm³]*	*8.0[cm³]*	*83%*

With two different examples, it is shown that the proposed method works robustly and can reduce the support structures with significant improvement.

6. Conclusion

CAD models that consist of large overhangs result in fabrication of large support structures resulting in wasted material and high buy to fly ratios. In this paper, a pre-fabricated reusable support structure system which minimizes the fabrication of conventional support structures is introduced. When an overhang is to be fabricated, modular support blocks are stacked under the overhang with a robot arm until the overhang of the model is reached. After the support structure strategy is formulated, The Robot program is generated and integrated into the existing AM G-code. To verify the improvement of the proposed strategy, two models are simulated, and the results are compared to the conventional methods. Minimizing the fabrication of support structures, the material can be reduced by 75% on average, which also results in a reduction in fabrication time.

7. Acknowledgements

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8. References

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