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ABSTRACT

Machine simulation is an effective way of checking additive manufacturing tool paths for both interferences and errors in part produced. This paper presents an algorithm to visually simulate a multi axis additive manufacturing system as it executes a process plan. Simulation results are intended to be used as a verification step before physically producing the part. Verification is particularly important for large builds of expensive materials. The algorithm uses an octree approach to efficiently model the deposition of part geometry and its changes. This paper discusses development of the simulation algorithm, including both the representation of the additive manufacturing machine and the octree data model of the part being produced.

1 INTRODUCTION

Rapid prototyping also known as solid freeform fabrication, is one of the widely used techniques for visualization in industries. By using rapid prototyping methods, prototypes can be completed rapidly by adding and bonding materials layer wise [2,6]. Some factors that would not allow additive fabrication are: specific material need, end use requirements, or explicit tolerance demands. In such a case subtractive manufacturing is used.[10] But rapid construction of physical models before real life production is of grave importance due to the need of the hour 'cost and time reduction criteria' as well as 'quality increment'. [7] This paper investigates an octree approach to produce a rapid prototyping model.

Information about 3D surfaces/models can be stored in an Octree and hence they can be used to represent a solid model. Octrees have particular advantages over other representations when the volumes contained are highly connected or *blobby* [4]. Briefly, the octree data structure is a tree composed of *octants*. Each octant defines a cubical volume and each octant will possess its own data wherein every cube is denoted as empty, full or neither (i.e., partially full). Octants that are partially full have eight child octants again and these child octants together exactly fill the space occupied by their parent. Like its parent, each child octant may be empty, full or divided into another eight octants [1, 4, 5]. Refer to Figure1, wherein the parent geometry is divided into eight octants namely C1, C2, C3, C4, C5, C6, C7 and C8. Octant C1 is partially full and hence is again divided into another eight octants. C1 is now a parent to octants – 1, 2, 3, 4, 5, 6, 7, 8. The octants C2, C3, C5 and C7 are full whereas octants C4, C6, and C8 are empty. This process is recursively continued until all octants are described in terms of empty or full octants with a certain degree of resolution.

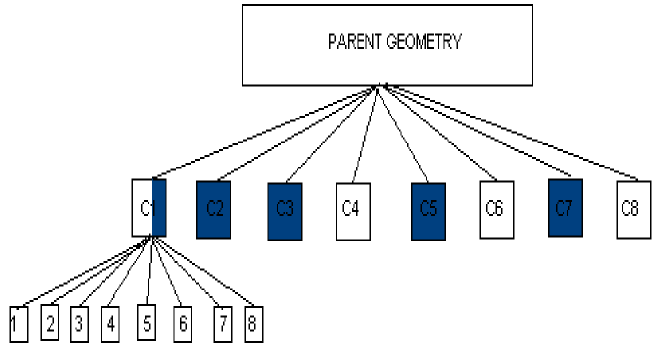

FIGURE 1. DIVISION OF A GEOMETRY BY OCTREE METHOD

Octree decomposition: The object that needs to be decomposed is enclosed by the smallest possible box so that it completely contains the entire object inside it. This cube is then divided into 8 sub-cubes and each of them is again either divided into octants or the subdivision is not performed as per containancy.[5] There is a set level of so as to determine the final size of the smallest octants.

Laser Aided Manufacturing Process (LAMP) lab uses a Fadal 5-axis CNC machine (model VMC3016) as shown in Figure 2, as the motion driver. The deposition nozzle is mounted at the side of the spindle, which forms a hybrid manufacturing system on a single workstation. These are used to restore a damaged part to its original geometry. [9]

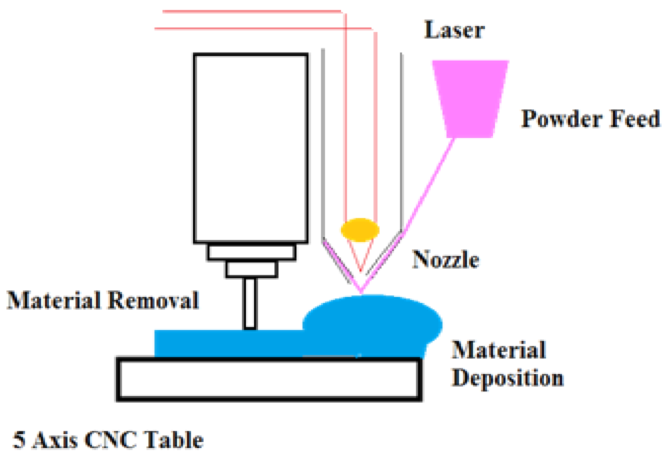

FIGURE 2. LASER METAL DEPOSITION PROCESS

This paper aims to address the difference between octree method for subtractive and additive manufacturing, visualization of the original geometry and division of the damaged surface into octants for the purpose of reconstruction using the octree approach. The paper will summarize how each geometry can be represented in a generic format using a text document, presents a pseudo code for octree additive operation and also explains the reason for conversion of a CAD model into STL format for this method.

2 RELATED WORK

Rapid prototyping is a different way, compared to conventional means, for manufacturing parts which are difficult to produce using general methods. Complicated shapes and geometries can be easily manufactured using solid freeform fabrication. However this is possible easily with the use of voxel modeling. This paper aims at using a voxel based octree method for the layer based production.

Octree decomposition has been in application since a long time from now, for subtractive manufacturing. However applying octree method on additive manufacturing is a challenge due to its different nature.

A major problem that comes across with the use of simulation for layered manufacturing is that these geometries can be fairly large in size and the size is unknown for an estimate. In case of octree decomposition, the size of the geometry is known and hence the size of the bounding box for the same can be decided and then recursive division of this box into octants happens until a desired resolution is reached. Refer to Figure 3, where A is the geometry with known dimensions and B is the bounding box that encloses the shape.

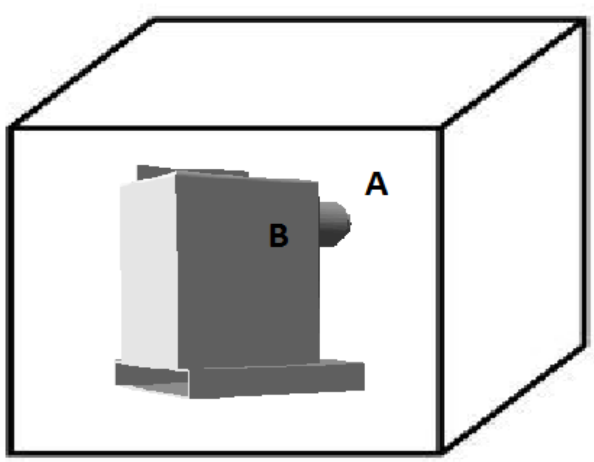

FIGURE 3. ILLUSTRATION OF BOUNDING BOX

The ordinary octree implementation begins with a single octant and unfortunately, this scheme does not allow for modelling of objects that grow or objects that appear outside the original working volume. That is because generally there is a CSG model or some kind of representation of the object from which its octree structure is derived.

Current visualization for additive manufacturing has the following disadvantages:

1) High computational time

2) High cost related process

3) Large amount of memory space is used for data storage in the case of layered manufacturing

This paper aims at overcoming the above disadvantages. In this paper, a generic method has been developed to represent the very first octant for any geometry in the form of numbers and letters in geometry input document, addition of parent octants and division and sub-division of the existing octants into several children and the advantages and disadvantages of this method are described.

3 CONCEPTS OF THE ALGORITHM

This paper discusses the following concepts

1) A 3D CAD model of the geometry

2) An octree data document

3) The implementation of layered addition.

The details about each of the above will be discussed in different sections in the paper. The flow of data, represented in Figure 4 below, is as follows – the 3D CAD model undergoes a transformation to STL format, in order to make it compatible with the solid freeform fabrication defacto standards after which it undergoes another set of transformations as per the algorithm and the data document in order to give the desired results.

The CAD model of the geometry is converted into STL format for ease of use. A geometry input format containing the initial size of the octree and the desired resolution, the two of which are inputs from the user is noted. The algorithm which helps in octree division and octant building is used resulting in the desired geometry in the form of octants.

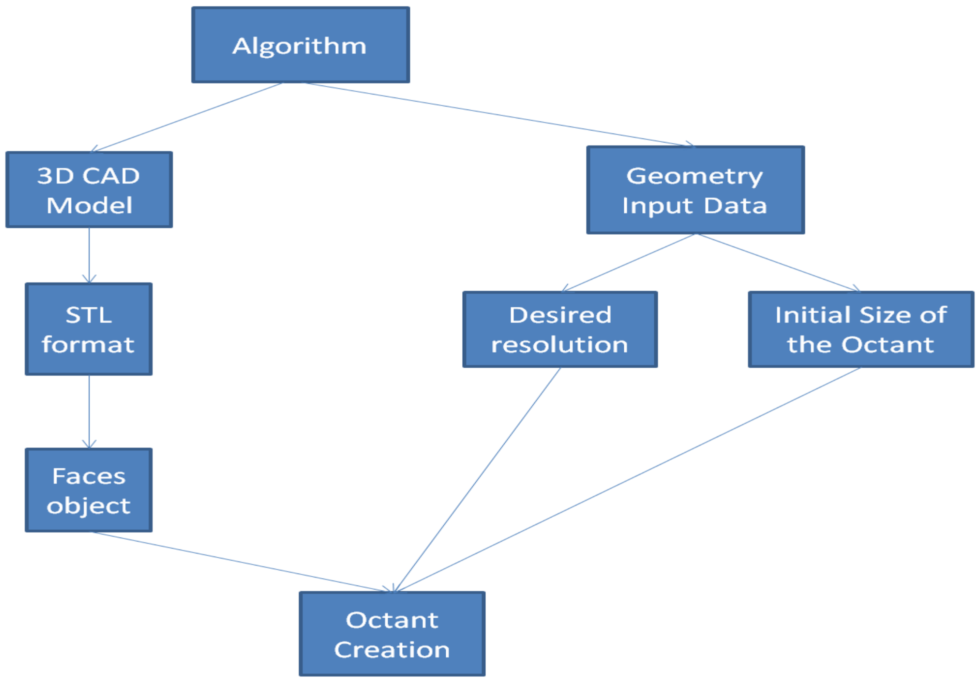

FIGURE 4. FLOW OF DATA

4 3D CAD MODEL TO STL FORMAT

The introduction of the first commercial SFF technology, stereolithography, was accompanied by the introduction of STL, a descriptive format to specify the solid shape to be produced. STL has become the de facto standard exchange format for the SFF industry. STL is faceted, the facets being triangles [1], as shown in Figure 5. In this Figure the front surface is depicted in the form of triangles. Such STL files are transmitted as three 3-D vertex coordinates and a normal vector. Using the 3D CAD model of a geometry to be made using octree approach, data needed for the actual dimensions of the part is known. This is important in order to compare the results of the octree based building and in turn becomes a verification step.

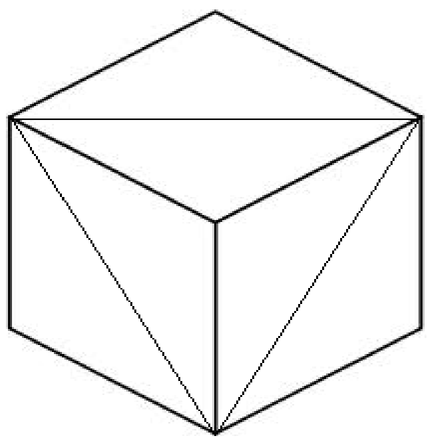

FIGURE 5. STL SURFACE DEPICTION

Most Rapid Prototyping machines, require polygonal models in STL format as the input solids. The CAD model as shown on the left side of Figure 6 is transformed into a faces object as shown on the left side of Figure 6, which is an array primitive consisting of one sided triangles.

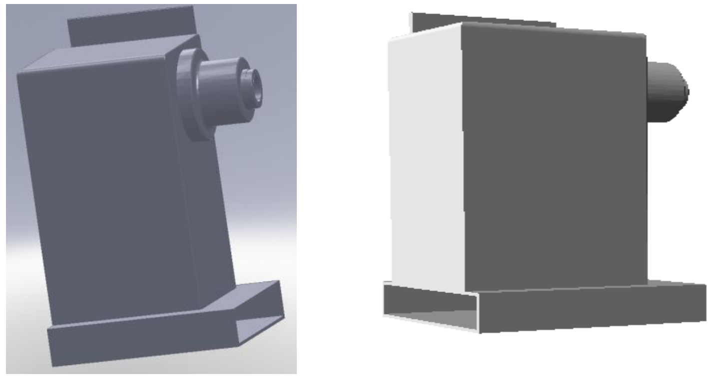

FIGURE 6. CAD MODEL & FACES DEPICTION

5 GEOMETRY INPUT FORMAT

Table 1 illustrates the input format for the generic representation of geometry. This format contains data in columns with each column separated by a tab space. Below is a list of the data contained in each column against the respective column numbers.

1 The initial size of the octant
2 The desired resolution until which the octree building must take place
3-5 The origin of the first octant in local co-rdinates(X, Y, Z), that is the co-ordinate frame of the part.
6-8 The colors in the form of vectors, that is, in RGB format.
9 The names of the geometry files.

The first column in table 1 consists of the initial size of the octant defined by the user as '5 mm^3'. The second column shows the maximum resolution until which the octant addition must take place. As per the table it is '40 mm^3'. This means that Octant building can be done 1 more time at the maximum. The number of times octant addition actually happens depends upon the part volume. The origin of the first octant is defined by the user in columns 3 to 5 as '1 0 0 '. The color of the octant can be given by the user in the form of a vector in columns 6-8 as '1 1 0'. The last column consists of the geometry file 'Y.STL' to be used for verification.

TABLE 1. EXAMPLE OF MACHINE CONFIGURATION

Initial Size Of Octant	Resolution	Origin			Color Vector			File name
5	**320**	**1**	**0**	**0**	**1**	**1**	**0**	**Y.STL**

6 ALGORITHM ILLUSTRATION

The proposed approach draws data from the geometry input file. The algorithm implementation is illustrated as follows. The first octant is made of the dimensions as per the initial volume size given in the geometry input document. Then a verification step takes place where it is found out if the bounding box encompasses the entire geometry or if the geometry to be created is outside the box.

In case the bounding box encompasses the geometry to be created as shown in Figure 3, no octant building takes place inspite of the desired resolution and this is because the desired resolution given by the user is to indicate the maximum number of times octant building can take place. However, the actual number of times the octant building takes place depends upon the geometry to be layered with just one rule that it should not exceed the desired resolution.

In case, the bounding box does not enclose the part geometry, another octant is created whose volume is eight times that of the initial octant. This becomes a parent to the initial octant. Seven more children are created for this parent octant, the eighth child being the initial octant. Six of the children are marked empty and the seventh child is filled with the data of the new geometry. This process is recursively continued until the desired resolution is reached or until the entire geometry is enclosed inside the bounding box. This entire process is depicted in the Figure 7.

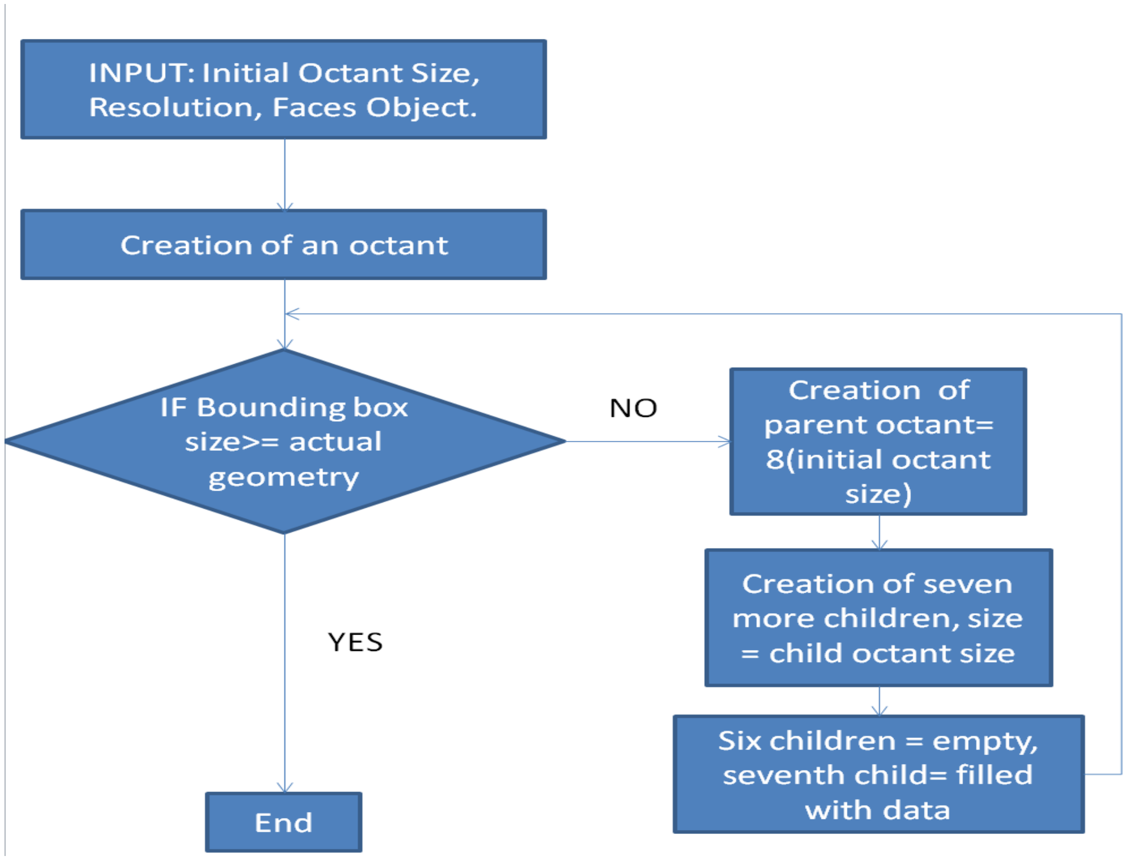

FIGURE 7. DEPICTION OF THE RECURSIVE PROCESS

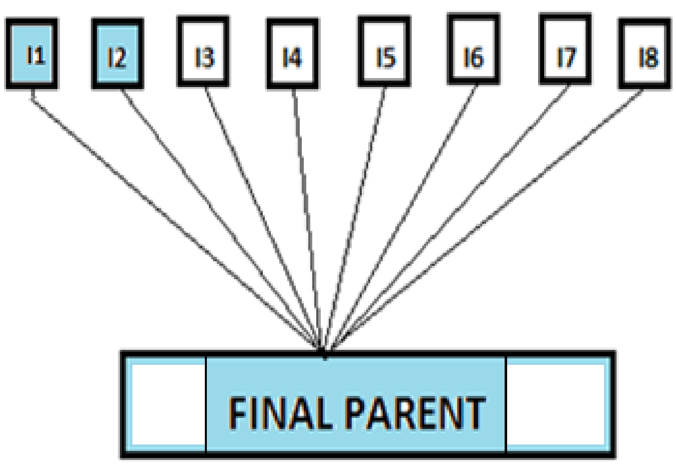

FIGURE 8. DEPICTION OF THE RECURSIVE PROCESS

As per Figure 8, I1 is the initial octant that is created. Since it does not enclose the entire geometry, another parent octant is created. Seven more children are created of the same size as the initial octant out of which six are marked empty- I3, I4, I5, I6, I7, I8. I2 consists of the data of the remaining geometry. I1 is also completely full. The final parent is partially full and hence it has children.

6 RESULTS & ADVANTAGES

The memory occupied by the six empty children is zero. Thus this method helps in saving memory space. All an octant consists of is its data in the form of pointers and usually an octant which is full occupies six bit of memory. The following is the pseudo code of the algorithm, wherein each function is described

Algorithm:

```
Oct_create
# 'creates an octant of dimensions of initial size of     the octant, specified by the user in the geometry data document'
for Oct_size==desired resolution or for Oct_size==dimensions of the geometry
Oct_box_Geo_check
# 'checks the geometry to see if the bounding box of the octant encloses the geometry recursively for the following conditions'
If Oct_box==Geo:
        End;
elseif Oct_box==desired resolution:
        End;
else:
        new_parent_Oct_create
# 'creates a new octant which is the parent octant, the size of which is 8 times the initial octant'
        new_children_Oct_create
# 'creates 7 more children of the initial size for the parent octant and makes six of them empty
        new_child_Oct_data store
# 'stores the data of the geometry that is not encompassed by the initial octant in one child'
```

FIGURE 9. DEPICTION OF THE ALGORITHM ON AN IMAGE

The above Figure 9, shows how an image is built by octree addition (left image). The image on the right [9] is the actual geometry. The octant building process can approximate curves to a large extent. However, it has to be made more accurate, so that the final image and the actual image are the same.

The most important properties of this method are:
(1) **Robust**: This method presents a general volumetric approach for approximating the surface of a solid defined by Boolean operations.
(2) **Accurate**: This method has an adaptive recursive octree addition and a related algorithm as well as a verification step to judge when the octree creation can be stopped. The reconstructed approximation is guaranteed to be topologically equivalent to the exact surface, and the approximation error is bounded by a user specification.
(3) **Efficient**: This algorithm is based on both uniform and adaptive cell representations.
(4) **Sharp features**: Sharp corners and edges can be captured as per user specification in the Booleanresults. It is especially suitable for engineering applications.[8]
(5) **User defined resolution:** The initial size of the octant and the desire resolution decide the accuracy with which the geometry is created.
(6) **Generic:** This algorithm can be applied and changes as per the user to any geometry.

7 CONCLUSIONS AND FUTURE WORK

Octree decomposition has been in use for the past two decades or more. But this concept was only applied to subtractive manufacturing. Using the reversal of octree decomposition, that is, octree addition for additive manufacturing is a relatively new approach. Octree addition is used for the depiction of layered processes where in there is geometric growth of the part. Thus in this paper a new octree based approach has been created for additive manufacturing representation wherein a verification process is also included and this helps as

1) An effective way of checking additive manufacturing tool paths for both interferences and errors in part produced.
2) The results are used to check the part geometry before physically producing the part as the materials are very expensive.
3) The algorithm uses an octree based additive approach to efficiently model the deposition of part geometry and also newly incorporated changes.
4) Also, this method is generic with more user defined features, thus making it more flexible and user friendly.

Another new concept in this paper is the generic format of taking user input. This makes it more user friendly and flexible.Future work for this includes improving on some of the following disadvantages:

1) Non-uniform data sizes in the octants because some areas of the input have greater detail [5]
2) In mechanical engineering, octree approach for additive manufacturing can be used for the verification of numerical command tool paths, for interference detection in five axis machining and in robotics.
3) The model does not yet acquire relatively high accuracy

The accuracy of the octree based layered method must be carefully determined, because if it is too high, it will dramatically increase computing time. Nevertheless, it must not be too small as well, as the part geometry then, cannot be accurately represented.

8 ACKNOWLEDGEMENT

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