

A METHODOLOGY FOR TOPOLOGY AND LATTICE STRUCTURE OPTIMIZATION OF
A CARGO DRONE MOTOR MOUNT

by

NAGADURGA SRINIVAS SRIPADA

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Abstract

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Nagadurga Sripada, MS

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Supervising Professor: Robert M Taylor

This work discusses a CAE driven methodology for designing a lightweight component by performing structural configuration on a given package space, creating a closed surface along this configuration using an interactive geometric modeling tool, and lastly generating lattice members that provide the required stiffness for the structure. The design process is explained starting with topology optimization performed on a single block with specific design constraints. It describes the effect of different parameters on the optimized results and how to analyze these results based on a given volume fraction constraint with the objective of minimizing the compliance. It then talks about why and how a free-form geometry is created using the interactive NURBS surfaces instead of directly using the topology optimized result. Lastly the effect of lattice member size on the total mass and stiffness of the component are studied. The results show that change in lattice cell type and size can cause the mass of the component to increase while the stiffness is reduced considerably.

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Chapter 1

Introduction

Additive manufacturing (AM) describes the technologies that build 3D objects by adding layer-upon-layer of material. Once a file is produced using a 3D modeling software, the additive manufacturing machine reads the data from the file and lays down successive layers of material to create a 3D object. [1] Objects of any complex geometry can be created using AM without any extra costs.

Design changes are introduced in all phases of the process. At a certain stage, changes to the concept is no longer possible. The concept phase plays an important role towards the efficiency of the design and the overall cost of the design development process. The overall cost can be reduced significantly by avoiding changes during the testing phase of the design. This is the major benefit of modifying the design process by introducing topology optimization. Topology Optimization is a conceptual design tool that can be used to enhance the design process. Mathematical calculations can be applied to get the results instead of using a concept based on estimations. [2]

AM also allows for complex parts with cellular and lattice structure implementation. The lattice structure geometry can be manipulated to deliver the level of performance required from the part. The development and research of different cell and lattice structures for lightweight design is of significant interest for realizing the full potential of AM technologies. [3]

A unique capability of 3D printing lies in its ability to manufacture porous shapes with complex external geometry using tiny cells known as lattice structures. [4] Lattice structures involve repetitive patterns of a particular cell shape or type. There are libraries

of cell types, and the density of these cells in a design is based on the application and loading that the design experiences. Apart from being unique to 3D printing, lattice structures bear some desirable characteristics from a design perspective. For example, due to the large network of structural members, the design exhibits better performance for stability. One promising application area is in energy absorption, in which lattice structures are used to cushion the loads imparted in rapid impacts, reducing the peak impact stress. The deformation characteristics of a lattice structure will depend on both its geometry and the material from which it is made. They also have desirable weight characteristics, and are used as an approach to target weight reduction. [5]

This work discusses a CAE driven methodology for designing a lightweight component by performing structural configuration on a given package space, creating a closed solid surface along this configuration using an interactive geometric modeling tool, and lastly generating lattice members that provide the required stiffness for the structure. The approach used in this work is to create a completely new motor mount design by defining a design space to help understand effective material layout by enforcing the same initial design constraints. Topology optimization is performed on this package space with the objective to minimize compliance with respect to a given volume fraction constraint. Optimization results for different volume fraction values is obtained and the model with the most clearly defined features is selected to perform further analysis.

As the result obtained has rough surfaces and the geometry is not smooth throughout a 3D modeling tool is used to interpret the topology optimized model. This is achieved by using an interactive NURBS surface tool which can represent the surface of the solid optimized geometry. This paper uses two different modeling tools created by SolidThinking: INSPIRE and EVOLVE. The first tool enables to build NURBS surface on

half the section of the optimized model. This tool is used as it can very efficiently create many small sections of the STL file as required and helps in combining the NURBS surfaces by creating a rough shape. The latter tool helps to redefine the features and create a uniform geometry by combining the design and the non-design parts together creating a water tight model. This water tight model is then imported into a lattice generating tool to build a lightweight structure. This work generates lattice structures with the help of Element Pro, a software by nTopology. A surface and volume lattice is created by defining the shape and size of the lattice members. These lattice members are then merged together using the same tool and exported into a finite element solver, here OptiStruct is used to perform linear static analysis on the model. Displacement results with varying element thickness is calculated and compared with the result of the original model.

Chapter 2 gives a brief discussion on the background of the methods implemented in this study. Chapter 3 talks in depth about the different methodologies used to create the lightweight structure. Chapter 4 shows the analysis and results achieved of all the processes employed. And lastly Chapter 5 discusses the conclusion and future work required.

Chapter 2

Background

This chapter discusses the use and application of a cargo drone, focus on the motor mount, and a brief introduction to topology optimization, lattice optimization, lattice structures, geometric modeling concept and the difference between each curve type.

2.1 Cargo Drone

The delivery of cargo with drones is a rapidly emerging field. As drones are flexible and deploy quickly, they can play an important role in last mile delivery. Delivery can often be carried out irrespective of ground conditions or infrastructure. Sever weather conditions still present important challenges for most platforms but even with weather delays, drones may offer cost savings over traditional delivery methods. Drones can provide more reliable and consistent deliveries, and multiple deliveries per day can improve the responsiveness of the delivery system. [6] A detailed discussion of the commercial application of drones is given in [7].

2.1.1 Application and current use

Several remote locations do not have access to all-weather roads. Healthcare providers and disaster relief responders depend on costly, slow, and unreliable transportation by motorcycles, cars, and trucks to serve communities. A VTOL (vertical take-off and landing) drone that can autonomously transport a given payload over 100-km to provide affordable, fast, and reliable delivery of vital goods to isolated areas, both on a regular basis and in times of crisis is thus very useful. With nearly 1 billion people around the world lacking proper medical care, small UAVs can be used to overcome the lack of

all-weather roads and rough terrain in order to transport diagnostic tools, lab specimens, and medications. UAVs are also valuable logistical tools for post-disaster care. [8]

2.1.2 Focus on motor mount

The cargo drone is a hybrid equipped with both wings and rotors. This hybrid configuration allows for vertical take-off and landing, and provides the drones with the ability to fly horizontally like fixed-wing drones. This means that they can cover longer distances and carry heavier cargo than multi-rotor drones. These hybrid drones look promising for cargo delivery where the combination of long flight time and vertical take-off and landing are important features. [6] Since the motor mount is one the major load bearing elements in the UAV it is thus the focus of this research.

2.2 Additive Manufacturing

Additive manufacturing (AM) is a method where a 3D object is created by adding material layer upon layer. Unlike conventional methods which removes material to create a part, AM creates the final shape by adding material. The development of AM technology started in 1980s. The implementation of additive manufacturing concept was first realized after a number patents were filed in 1984 simultaneously by USA, Europe (France) and Asia (Japan). All these patents described a similar concept of fabricating parts by selectively adding material layer upon layer. Hideo Kodama in his work [9] created the first 3D printing process. In 1984 André et al. [10] filed a patent for the stereolithography process, but the most influential work was by Charles Hull who filed his own patent 3 weeks later. In his work [11] Hull coined the term stereolithography and created an apparatus for building a 3D solid object. The French inventors were abandoned by the French General

Electric who claimed that their research lacked a business perspective. In 1989 Scott Crump and Lisa Crump invented Fused Deposition Modeling (FDM) technology. [12] FDM makes use of a thermoplastic filament which is heated to its melting point and then extruded layer by layer creating a 3D object. AM also has the flexibility of working with different materials and in mid 1990s considerable research began on metal 3D printing technologies. Since then a number of AM processes were developed which are described in detail by Gibson et al. [13] AM enables manufacturing light-weight parts and tools by creating lattice structures that consume less material while satisfying the strength and stiffness requirements of the component. AM thus has a great potential in creating customizable, cost effective, lightweight products.

2.3 Structural Optimization

This topic covers the background on Topology and Lattice Optimization. It also covers a brief description of lattice structures, their properties and importance in the building light-weight structures.

2.3.1 Topology Optimization

Topology Optimization is a technique which provides optimum material distribution within a given package space to obtain the best structural performance. An optimization problem can be expressed as shown in equation (1).

$$\begin{array}{ll}
\text{Minimize/Maximize} & f(x) \\
\text{Such that} & h_j(x) = 0 \quad j = 1, 2, \dots, n_h \\
& g_k(x) \leq 0 \quad k = 1, 2, \dots, n_k
\end{array} \quad (1)$$

Where h_j and g_k are constraints, j and k are the number of equality and inequality constraints. The seminal paper on numerical topology optimization was written by Bendsoe and Kikuchi [14] where the concept of homogenization approach to topology optimization was developed. Since then the concept developed in numerous different directions. The density method or the SIMP method was first introduced by Zhou and Rozvany. [15] SIMP stands for Solid Isotropic Microstructure with Penalization for intermediate densities. Rozvany performed a detailed evaluation and compared different numerical methods of structural topology optimization in his paper. [16] In 1993 a method called the Evolutionary Structural Optimization (ESO) was introduced by Xie and Steven. [17] ESO approach removes unwanted material gradually to achieve an optimal design. This approach was first developed for shape and layout problems with stress consideration and then for frequency optimization. Many structural shape and topology optimization solutions obtained by other complicated methods have easily been reproduced by the ESO method. Another concept developed was the level set method for structural optimization by Allaire et al. [18] This method performs a numerical analysis of the surfaces and the shapes of the objects. The level set model can handle changes in topology and can precisely describe the boundary shape of the structure.

OptiStruct solves topological problems using the density method, also known as the SIMP method. A modified SIMP method is chosen for solving the optimization problem.

The design region is discretized by square finite elements where each element e is assigned a density x_e and the Young's Modulus E_e is calculated as shown in equation (2)

$$E_e(x_e) = E_{min} + x_e^p (E_0 - E_{min}) \quad x_e \in [0,1] \quad (2)$$

Where E_0 is the material stiffness, E_{min} is used to prevent singularity of stiffness matrix, and p is the penalization factor. The singularity of stiffness matrix is avoided by imposing a lower limit slightly larger than 0 for the densities x_e . Material density of each element is used as the design variable, and the density varies between 0 (void) and 1 (solid). It is necessary that the material density of each element take a value of either 0 or 1. Element densities between 0 and 1 are considered fictitious material. The stiffness of the material is linearly dependent on the density. The optimal solution of problems involves large gray areas of intermediate densities in the structural domain. Such solutions are not meaningful when we look for the topology of a given material. Therefore, intermediate densities need to be penalized and the final design should be represented by densities of 0 and 1 for each element. The penalization technique used is the "power law representation of elasticity properties," [2] which can be expressed for any solid 3-D or 2-D element shown in equation (3)

$$\underline{K}(\rho) = \rho^p K \quad (3)$$

Where \underline{K} and K represent the penalized and the real stiffness matrix of an element, respectively, ρ is the density and p is the penalization factor which is always greater than 1. The mathematical formulation of the problem is given in equation (4) and is solved by using a standard optimality criteria method.

$$\begin{aligned}
\text{Min } x \quad & c(x) = U^T K U = \sum_{e=1}^N E_e (x_e) u_e^T k_0 u_e \\
\text{Such that} \quad & \frac{V(x)}{V_0} = f \\
& K U = F \\
& 0 \leq x \leq 1
\end{aligned} \tag{4}$$

Where c is the compliance, U and F are the global displacement and force vectors, K is the global stiffness vector, u_e is the element displacement vector, k_0 is the stiffness matrix for the element with unit Young's modulus, x_e is the element density, N is the number of elements and $\frac{V(x)}{V_0} = f$ is the volume fraction which is the design constraint here.

2.3.2 Lattice Structures

An advantage of using cellular materials is that they offer high strength accompanied by relatively low mass. Lattice structure is a type of ordered cellular material which can provide good energy absorption characteristics. Another type of cellular material is stochastic materials which have excellent thermal and acoustic insulation properties. Lattice structures comprise of unit cells that define their geometries and topologies. When the length of these lattice cells is in the range of 0.1 to 10 mm, they are referred to as mesostructured materials. Rosen et al. [19] employed a unit lattice finite element analysis method allowing non-linear deformation to analyze a unit cell comprised of n^3 unit structures for their stiffness and displacement compared to their relative density under loading. Deshpande in his work [20] pointed out that the strength of foam scales as $\rho^{1.5}$, whereas lattice structure strength scale as ρ , where ρ is the volumetric density of the material.

There has been considerable research on the effect of AM processes on lattice structures. Park et al. [21] studied the effects of the Electron Beam Melting AM process on geometrical and mechanical properties of fabricated lattice structures by comparing the strength of lattice structures designed using two methods: the uniform voxel based method and the conformal method. Lyibilgin et al. [22] investigated different lattice structures manufactured by fused deposition modeling (FDM) process. The shapes studied included honeycomb, square, diamond, triangle and circle. All the five lattice structures had higher strength with same porosity than the specimens using the sparse and sparse-double dense styles, but the lattice structures required significantly longer build times than the sparse and sparse-double dense styles.

Various lattice cell structures were also researched, Maskery et al. [23] explored the effects of cell size by examining the elastic modulus and ultimate tensile strength of latticed parts with a range of unit cell sizes and fixed density. Deshpande et al. [20] studied the mechanical properties of the octet-truss lattice structured materials. He found that the strength and stiffness of the octet-truss material are stretching-dominated and compare favorably with the corresponding properties of metallic foams.

There has also been a considerable amount of research based on the cell properties and their applications. Doyoyo and Hu [24] studied two microscopic parameters related to the geometry of struts: Strut-level strengthening and slenderness ratios. The results show that while both these parameters expectedly influence the size and shapes of the failure surfaces, they also dramatically alter microscopic deformation mechanisms leading to macroscopic failure. Labeas and Sunaric [25] investigated the response of three different cellular core types, and developed a methodology to study the structural response and failure process of open lattice metallic cellular cores. He assessed that the strut aspect

ratio, unit-cell spatial configuration and unit-cell size highly influence the structural behavior.

2.3.3 Lattice Optimization

Lattice Optimization is implemented along with topology optimization to help reduce the component mass. Defining lattice structures by manipulating the unit lattice cell shape and size enables engineers to design mechanical properties such as elastic modulus and yield strength for specific applications. Lattice structure is a type of cellular material comprised of a network of struts. Various methods for designing lattice structures have been proposed. Nguyen et al. [26] presented a method for efficiently optimizing Conformal Lattice Structures (CLS) by using a heuristic that reduces a multivariate optimization problem to a two-variable problem. This means that the stress distributions are similar in CLS and in a solid body of the same shape. Using a CAD software to design lattice structures is time consuming and inefficient, McMillan et al. [27] developed an open source method of generating periodic lattice structures directly to the generic STL file format. This programmatic method offers a huge advantage to designers seeking to conduct FE simulations on lattice structures allowing a batch export of both STL parts and a geometrically equivalent FE beam models. A size matching and scaling synthesis method for the design of meso-scale structures was developed by Chang and Rosen [28] The strength of the lattice structures designed was compared by Park et al. [21] using two methods: the uniform voxel method; which divides a part into unit volumes and maps lattice topology into those volumes, and the conformal lattice structure method; used for constructing lattice structures whose unit cells are constructed parallel to the surface to be reinforced. Designing light-weight lattice structures is a problem of design for rigidity. Chu et al. [29] compared two optimization algorithms: Particle Swarm Optimization (PSO) and

Levenburg-Marquardt (LM), based on a least-square minimization formulation. It was found that LM was a more viable algorithm for optimizing structures of complex geometries for minimum weight and desired stiffness.

This paper makes use of a lattice generating tool called Element Pro a software developed by nTopology to perform the lattice optimization. A study of how new lattice types and member sizes are generated and their effect on the overall mass and displacement are discussed in Chapter 3.

2.4 Geometric Modeling

The next step after the structural optimization is to create a free form solid model on the topology optimized result. This topic gives a brief introduction to geometric modeling, the different modeling tools used and the application of NURBS in this paper.

2.4.1 Geometric Modeling background

Early work in nonrational free-form curves and sculptured surfaces, using the cubic Hermite interpolation scheme was initiated by Coons [30] and Ferguson [31]. A widely used method for curve design was developed by Bézier [32], [33] which consisted of nodes with attached control handles. The user can manipulate the shape of the curve on either side of the common node which is defined by these control handles. de Boor [34] and Cox [35] laid the foundation for B-splines, they both independently developed an algorithm to overcome the problems of numerical instability based upon straightforward calculations of alternate definitions of B-splines. Gordan and Riesenfeld [36] presented the use of this algorithm for various computations and described the procedure for evaluating B-spline

functions. Rational formulations of the Bézier and B-spline followed soon after, culminating in the very powerful and popular NURBS curves and surfaces (nonuniform rational B-splines). A brief discussion of three different free form curves is described below.

2.4.2 Hermite Curve

The cubic Hermite curve and bicubic Hermite patch were the earliest forms investigated in geometric modeling. Hermite curves are a special case of Bézier and B-spline forms. Interpolation in this curve is not restricted to points for example a cubic Hermite curve is defined by its two end points and the tangent vectors at those points. [37] However, due to the lack of invariance under affine transformations it is the least favored free form curve. Figure 1 shows an example of a Hermite Curve.

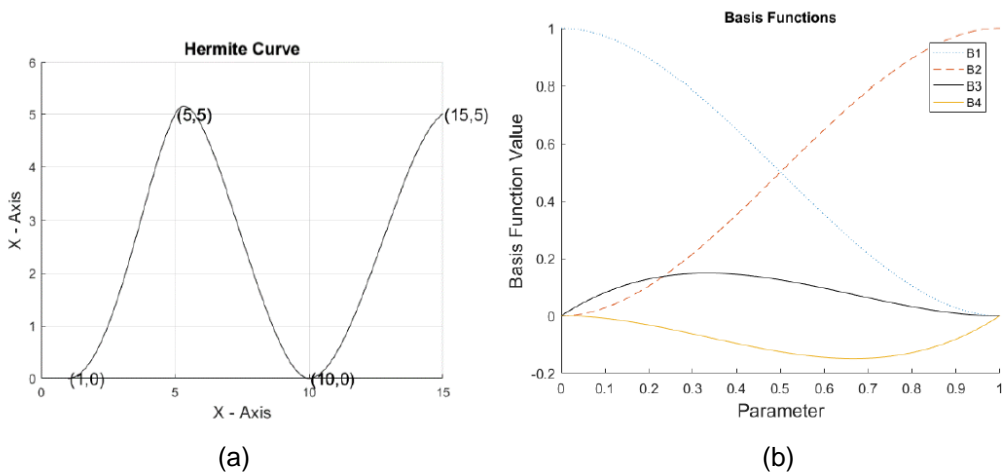


Figure 1: Hermite Curve example (a) Hermite Curve and (b) Hermite Basis Function, [38]

2.4.3 Bézier curve

Bézier curve exhibits a convex hull property and the curve form is the easiest to subdivide. This curve is defined by a set of control points which influences the shape of the

curve. However, the Bézier curve does not offer a local control and change in any control point propagates throughout the curve. [37] Figure 2 shows an example of the Bézier curve.

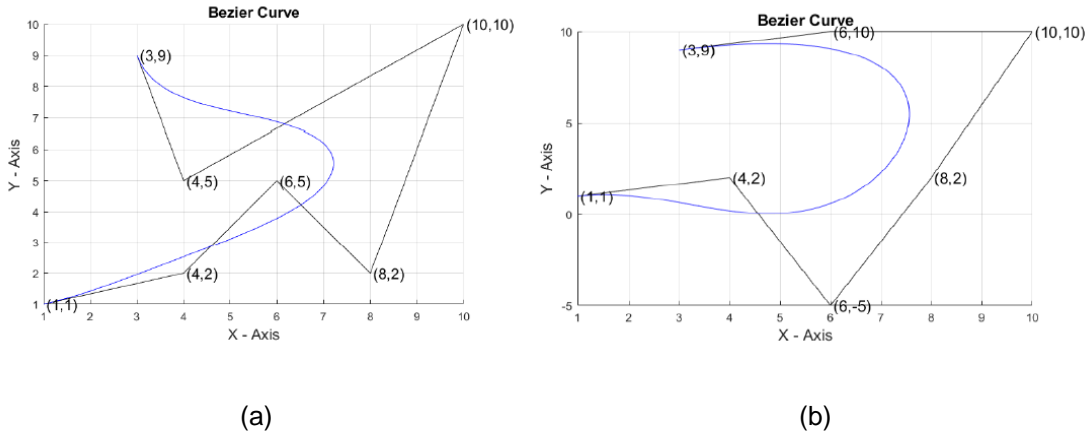
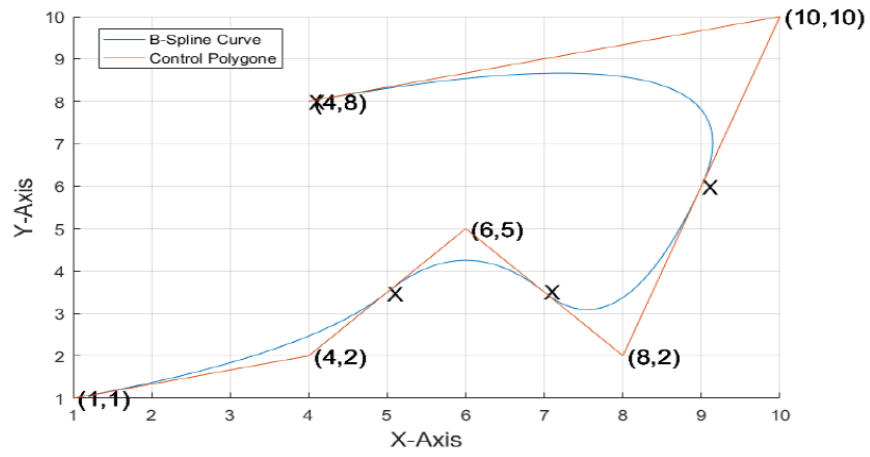


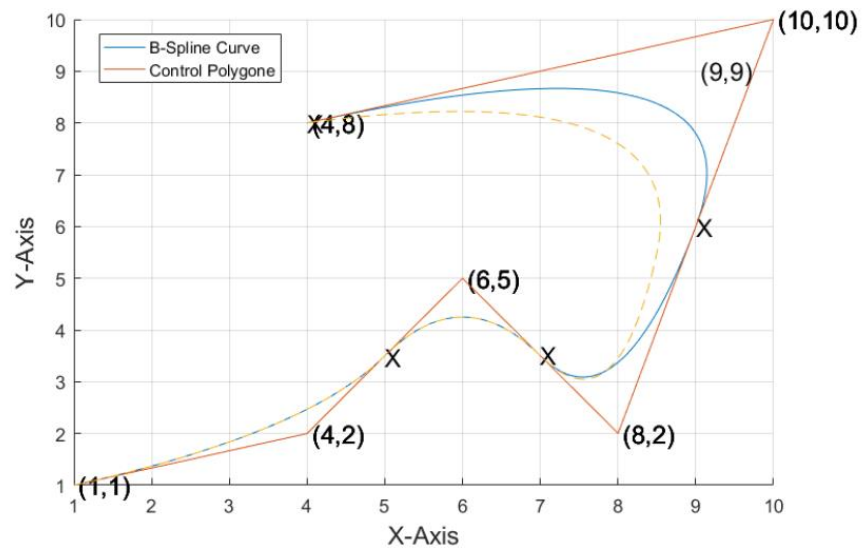
Figure 2: Bézier Curve example (a) Bézier Curve and (b) Modified Bézier Curve, [38]

2.4.4 B-spline curve

B-spline curve is a piecewise polynomial curve defined by a set of control points. A B-spline curve differs from Hermite or Bezier curve as it consists of more than one segment, where each segment is defined by a few control points. The degree of the curve is independent of total number of control points. [37] This allows change in shape which is not propagated beyond a few local segments. B-splines do not necessarily interpolate their end points, but the nonuniform B-spline basis functions allow this. Figure 3 shows a B-spline curve, Figure 3 (a) shows a clamped B-spline curve and Figure 3(b) shows the modified clamped B-spline curve where the control point moves from (10,10) to point (9,9), the dotted line shows the new curve and continuous line is the old curve.



(a)



(b)

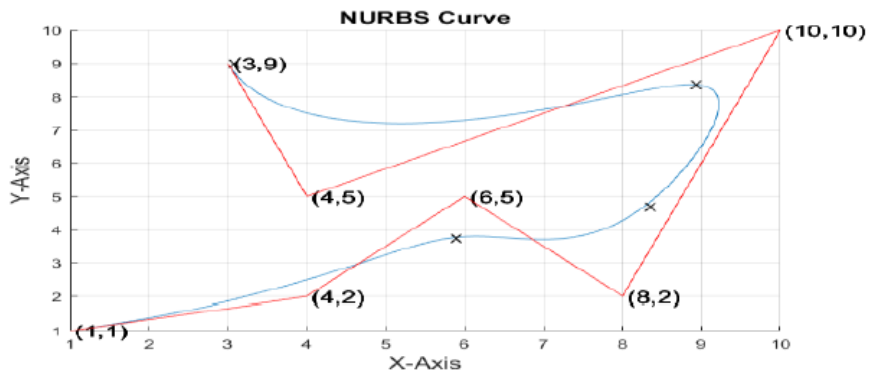
Figure 3: B-spline curve example (a) Clamped B-spline and (b) Modified Clamped B-spline, [38]

2.4.5 NURBS (Nonuniform rational B-splines)

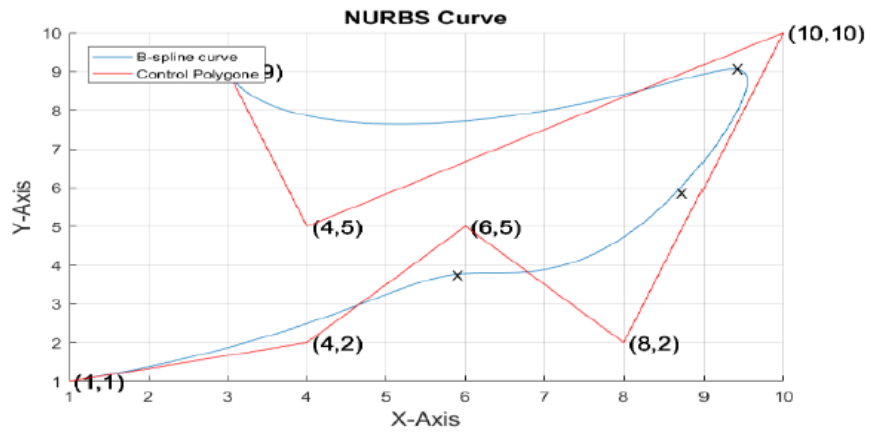
NURBS is one of the most versatile tools for modeling curves. It is a ratio of two nonrational B-spline basis functions, making it a vector-valued piecewise rational polynomial. NURBS curves are invariant under geometric transformations. Like rational Bezier curve, nonuniform rational B-spline curves can be used to represent exactly the conic curves with the advantage of local control. [37] Points on a NURBS curve are given by equation 5.

$$\mathbf{p}(u) = \frac{\sum_{i=0}^n h_i \mathbf{p}_i N_{i,K}(u)}{\sum_{i=0}^n h_i N_{i,K}(u)} \quad (5)$$

Where the h_i are the weights, \mathbf{p}_i are the control points and $N_{i,K}$ are the nonrational B-spline basis function. There are three ways to modify the shape of a NURBS curve: change the knot vector, move control points, and change the weights. Because it is relatively difficult to determine how a curve will respond to changes in the knot vector, this is not the best way to change curve shape. On the other hand, the effect of changing a control point is predictable and intuitive. If a weight h_i is increased or decreased in value, then the curve is pulled toward or pushed away from, respectively, the control point \mathbf{p}_i . Weight changes will move any point on the curve along a straight line through its corresponding control point an example of which is shown in Figure 4.



(a)



(b)

Figure 4: Example of NURBS curve (a) NURBS curve with weightage 2 on the control point (10,10) and (b) NURBS curve with weightage 4 on the control point (10,10), [38]

Chapter 3

Methodology

The methodology for designing a stiff and lightweight structure for a motor mount is discussed in this chapter. An overview of the methodology is shown in Figure 5. It describes in detail how topology optimization is performed and how the different parameters affect the optimization result. It then goes on to describe the reason for creating a NURBS surface and shows how it is effectively used. Another important topic covered here is lattice generation, in which a surface and volume lattice is created and then thickened.

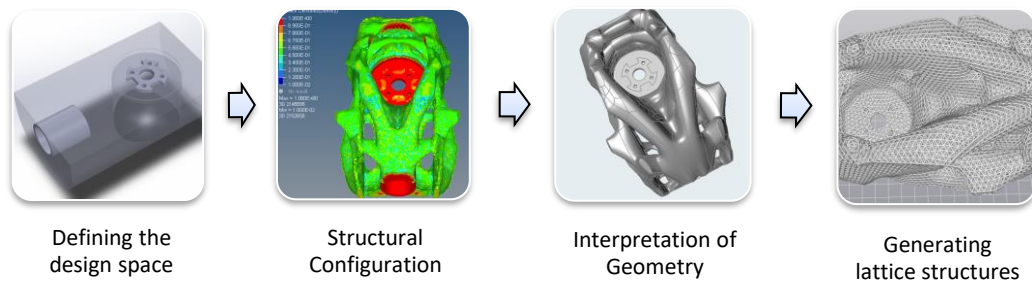


Figure 5: Methodology for designing a lightweight stiff structure

3.1 Structural Configuration

A drone motor mount is considered in this research as it is one of the major load bearing elements in a drone, and the effect of varying topology optimization parameters is studied. Figure 6 shows the original (conventional) design of the motor mount.

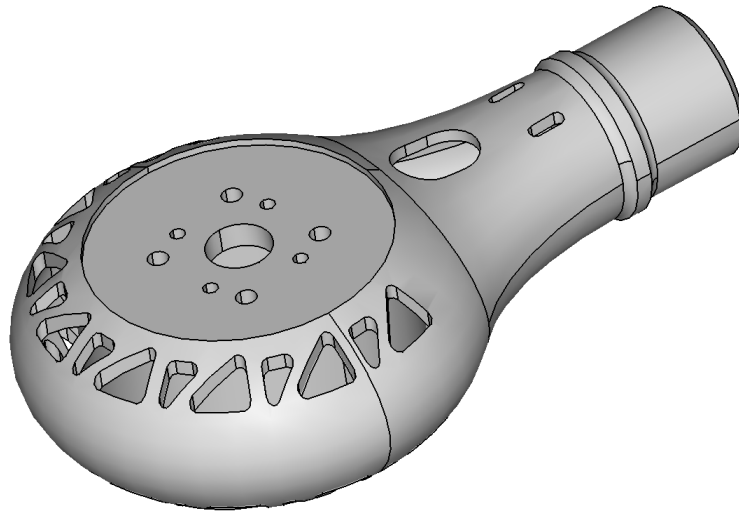


Figure 6: Original motor mount design, [39]

For the purpose of this research a single block with dimensions of the original package space is being considered as shown in Figure 7. This block was created in a CAD software and imported into OptiStruct as a STEP file. The green region is the design space and the blue region is the non-design space. A fixed constraint is placed at the mount rod interface and a vertical load of 17 lbs is acting on the block as shown in Figure 8. The objective of topology optimization is to minimize the compliance for a given set of design constraints.

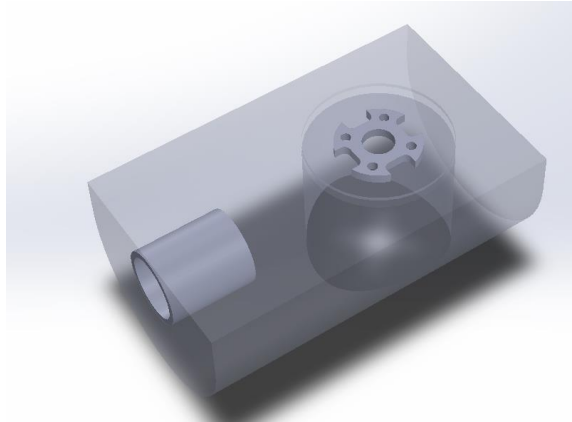


Figure 7: Defining the package space using a CAD software

Hypermesh is used as the preprocessor and OptiStruct is the solver which is based on the DRCO (**D**esign variable, **R**esponse, **D**esign **C**onstraint, and **O**bjective) approach.

[2]

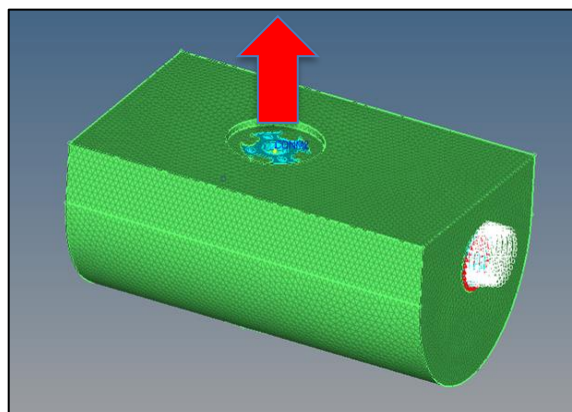


Figure 8: Motor mount prior to topology optimization

This topic studies the important parameters of topology optimization and their effect on the optimized result. It also covers the topology optimized results based on

different volume fractions and member sizes, and the basis for selecting suitable topology optimized result for further analysis is discussed.

3.1.1 Topology Optimization Parameters

A topology optimization problem first requires a finite element model, in this paper OptiStruct is used to perform this operation by defining the design and non-design space, material used, the property associated with each component and assigning the load and fixed constraints on the model. The next step is to define the design variable. OptiStruct uses a density based approach to solve a topology optimization problem. Density of each element is taken as the design variable. Here each element must take a density value of either 0 (void) or 1 (solid) and any element density in-between is considered as a fictitious material which are not meaningful in topology solutions. These material densities are penalized and the final design is forced to have densities of only 0s and 1s. Penalization of the intermediate densities is a critical topology optimization parameter. The setting corresponding to the penalty factor is known as DISCRETE and is related to the penalty factor as $DISCRETE = (p-1)$. Varying the DISCRETE parameter helps achieve a clearer structure.

Two internal responses: volume fraction and weighted compliance are used for this optimization. Both these responses are global and are defined for the whole structure. Volume fraction is another important topology optimization parameter that controls what volume fraction of the initial design domain is used in the optimized structure. Volume fraction response has values between 0.0 and 1. This response considers only the design volume in the fraction calculation. A specific volume fraction is used as the constraint here. The formulation for volume fraction [2] is given as shown in equation 6.

$$\text{Volume Fraction} = \frac{(\text{total volume at current iteration} - \text{initial non-design volume})}{\text{initial design volume}} \quad (6)$$

The objective of the topology optimization is to minimize the compliance for the applied load and boundary conditions. Weighted compliance response is used to define the objective of this problem. Weighted compliance is a method used to consider multiple subcases (loadsteps, load cases). The response for this model is the total compliance of the single load acting on the block.

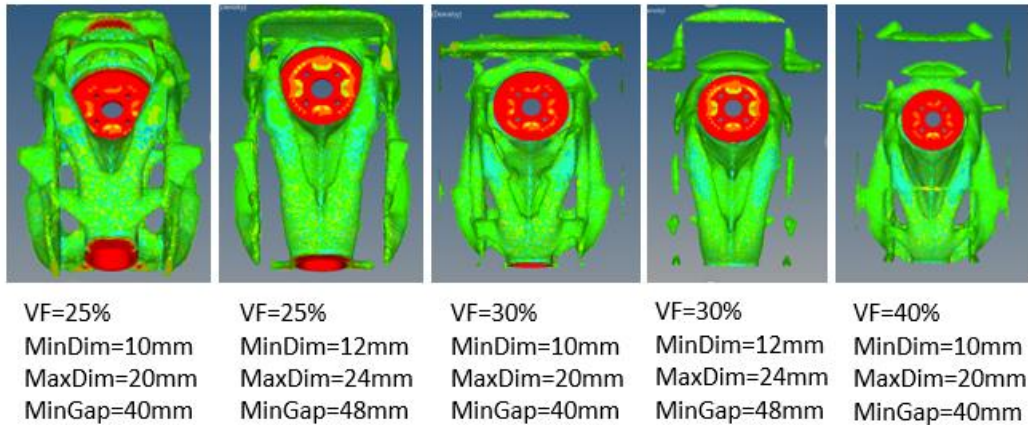


Figure 9: Difference in topology results by varying volume fraction and member size

Another parameter that influences the topology optimization result is the minimum member size. This parameter constrains the minimum diameter any member of the structure is allowed to have. Minimum member size control functions more as a quality control than a quantity control. Checkerboarding, which means a pattern of high and low value density areas, is suppressed and clearer results are obtained. A checkerboard is undesirable as it is a result of numerical instability and does not provide an optimal material distribution. It is recommended that MINDIM be at least 3 times, and no greater than 12

times the average element size for all elements. [2] An example of the effect of these parameters on the optimized result is shown in Figure 9.

3.1.2 Topology optimization result interpretation

Topology optimization results with a range of volume fractions were calculated each having different member sizes. Even though the member size and volume fraction is being varied the details in the design may vary but all lead to the same conceptual design as shown in Figures 10 and 11.

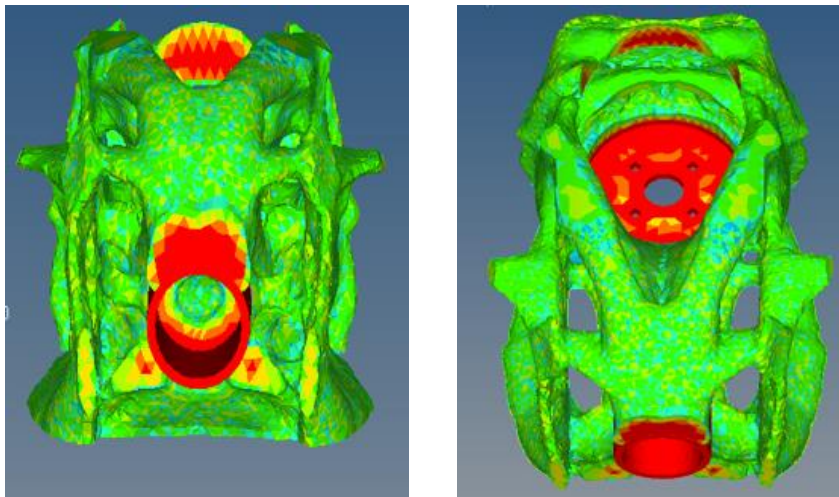


Figure 10: Topology Optimization result for 25% Volume Fraction

Figure 10 shows the topology optimized result for 25% Volume Fraction with a Minimum dimension of 10 mm and Maximum dimension of 20 mm and Minimum Gap as 40 mm. The green region show elements with lower density and the red region shows elements with a higher density. As seen from the Figure 10 the model has a continuous

boundary. The structural features are clearly defined and the member size throughout the structure seems to be uniform without any discontinuities. This model can be easily manufactured. Figure 11 shows the optimization result for different volume fractions (VF) all having the same minimum dimension as 10 mm, maximum dimension as 20 mm and minimum gap as 40 mm. The optimized result with 30% volume fraction was not considered as there is discontinuity in the structure and is not an optimal design that can be manufactured. The optimized result for 35% volume fraction also has a lot of discontinuity, all features are not clearly defined.

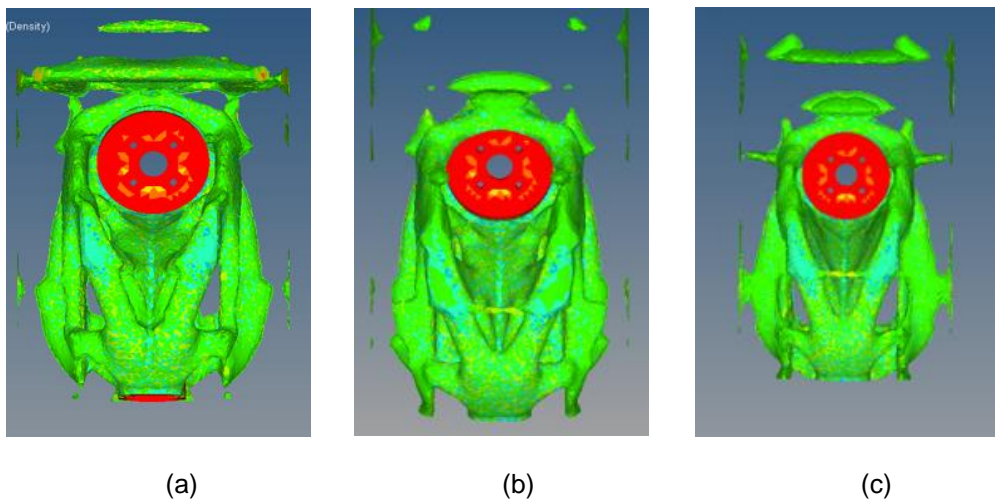


Figure 11: Topology Optimization result for (a) 30% VF, (b) 35% VF and (c) 40% VF

Now considering 40% volume fraction, the optimized result does not have a uniform member size, the elements are disconnected and features are very poorly defined. This result is also not suitable and the part will be very difficult to manufacture.

3.2 Geometric Modeling

This topic gives a brief introduction to the tools used for creating the NURBS. It goes on to discuss why NURBS are used to create a free-form model representing the topology optimized result and how the tools are used effectively to create an organic model.

3.2.1 Software tools used to create NURBS

This paper uses INSPIRE a software developed by SolidThinking which was acquired by Altair. It allows design engineers to create structurally efficient concepts quickly and assists in creating new geometry within the given package space using loads as an input. This software also helps in creating complex surfaces using the topology optimized result. INSPIRE has the benefit of working with EVOLVE which is also another industrial modeling software developed by SolidThinking used as a hybrid modeling and rendering tool to develop forms faster. This modeling software provides more organic surface modeling and parametric control of the NURBS surfaces as compared to the former software. It is used in this work to refine and fine tune the NURBS features that were created in INSPIRE.

3.2.2 Interactive NURBS vs traditional CAD software

A CAD software is generally used to define an object having a solid shape which has a certain amount of volume. The CAD programs make use of 2D drawings and help translate them into 3D objects, but it may not give a direct control for a free-form design. A modeling software on the other hand is used to represent the skin of a solid surface and it contains no volume. The modeling software is based on surfaces created from a 3D

geometry. The advantage of modeling over CAD is that it is very interactive and lets the users access each vertex or surface individually or as groups.

As the topology optimized results obtained are very noisy, it is difficult to manufacture the part directly due to its complex geometry and rough surfaces. A modeling software is thus used to create an organic shape that exhibits a smooth geometry and is easily manufacturable. As the NURBS curve is the most versatile tool for modeling curves it is used to create the free-form model. A new modeling concept known as PolyNURBS was introduced by SolidThinking that allows to trace over an optimized result with ease and efficiency. Although NURBS curves and surfaces are precise and flexible for modeling, polygons offer certain advantages. PolyNURBS combine the ease and simplicity of polygonal modeling with the precision and flexibility of NURBS, allowing the user to quickly create free-form solid geometry that is smooth and continuous. The object thus created represents geometry as a NURBS surface surrounded by a transparent, quad-only, polymesh cage. The shape of this object can be manipulated using the cage's faces, edges, and vertices.[40] This modeling method allows the user to create a smooth, watertight NURBS version of the STL geometry

3.2.3 3D Modeling using NURBS

The topology optimized result is imported as an STL file into the modeling software to create a smooth organic shape along the optimized geometry. This paper uses the tools provided by Altair to create the free-form geometric model. Initially the INSPIRE software was used to create the NURBS as this tool provides a section feature that is not available in EVOLVE for an imported STL file, and the latter software was used to define the features

clearly and merge design and non-design space. Figure 12 shows the optimized result imported as an STL file.



Figure 12: Optimized result imported as an STL file

To start creating a NURBS surface we select the feature as shown in Figure 13, this feature is quite straightforward and easy to use.



Figure 13: NURBS feature on 3D modeling tool called INSPIRE

NURBS are created by wrapping along the optimized contour by creating small sections of the STL file, multiple NURBS can be created and then bridged to build a body as shown in Figure 14.

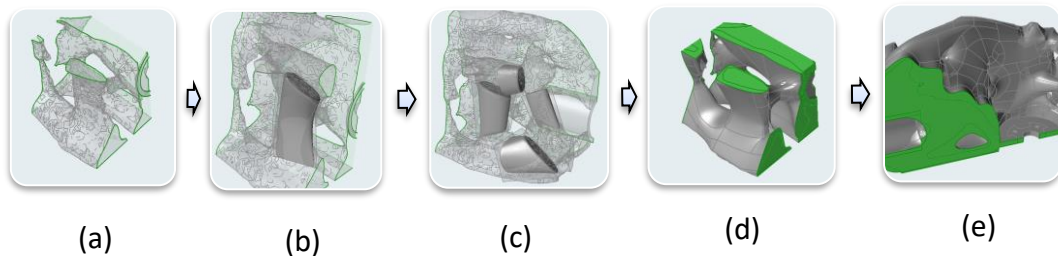


Figure 14: Process followed for creating the NURBS

Figure 14(a) is created by using the section tool in INSPIRE. The section tool as shown in Figure 15 allows to create multiple small sections of the STL file, you can choose to hide and unhide any section while creating the free-form geometry. This is one of the main advantages and prime reason to work with INSPIRE as it is the fastest way to build the NURBS to create a rough shape which can be fine-tuned in EVOLVE. Here as seen in Figure 14(b) – 14(e) the NURBS are created on half the section of the STL file and then imported into EVOLVE to mirror and combine the design and non-design parts.

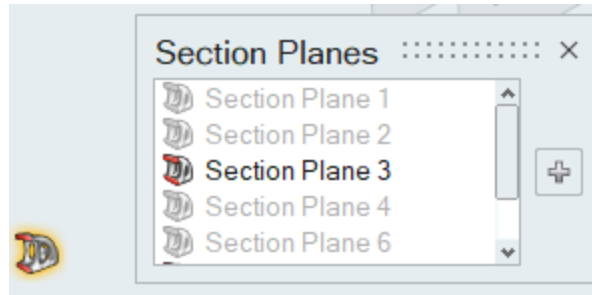


Figure 15: Section feature on the 3D modeling tool

You can also choose to hide or unhide individual NURBS surface in the model browser to make changes to their shape as shown in Figure 16.

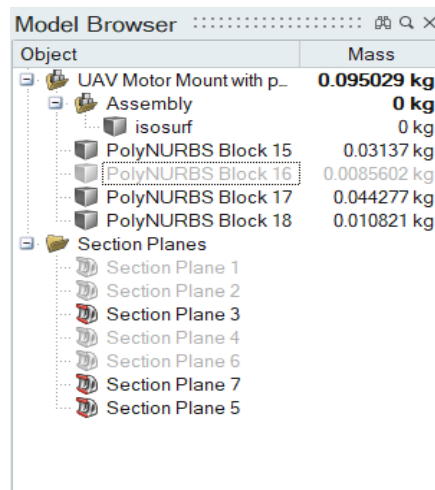


Figure 16: Hiding individual NURBS

While creating NURBS surfaces in INSPIRE is straightforward, there are many errors like face overlapping, ghost vertices etc. which do not show up. Due to these errors a closed solid model is not created and the part cannot be manufactured as it is not a watertight model.

After creating NURBS on the entire part, the design engineer still cannot be sure that all the surfaces are closed or not overlapping as there is no way to check for these errors in INSPIRE. The model shown in Figure 17 was exported into EVOLVE and here we can ascertain which faces are overlapping and how to correct them. This is a cumbersome process as any change made to separate faces will change the shape of the model and symmetry of the model is not maintained.

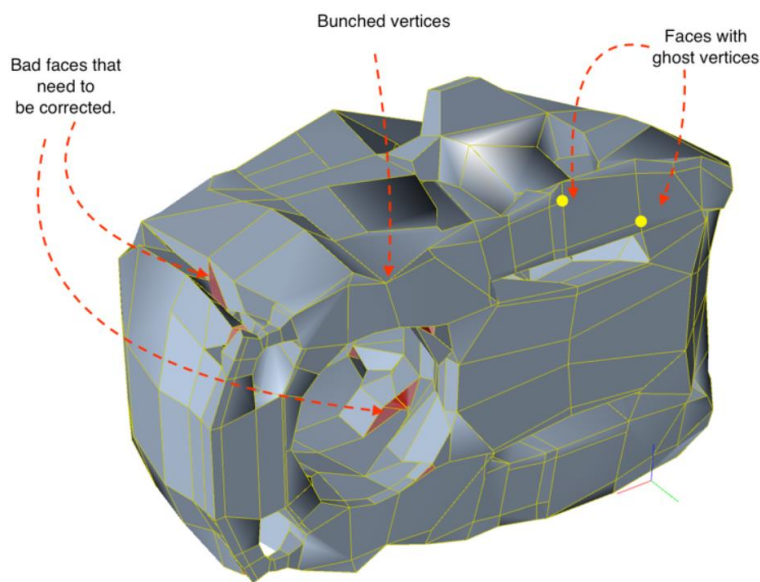


Figure 17: Unknown hidden errors after creating NURBS surface model

The general rule of thumb while creating the NURBS surface using this tool is to keep the faces 4 sided and in some cases 3 sided (an exception). 5, 6 sided faces are problematic and difficult to handle. The vertices should also be checked for bunching as shown in Figure 17. Inspire does not catch errors of hidden faces in the model as shown in Figure 18, leading the design to consist of complex shapes with inconsistent geometry.

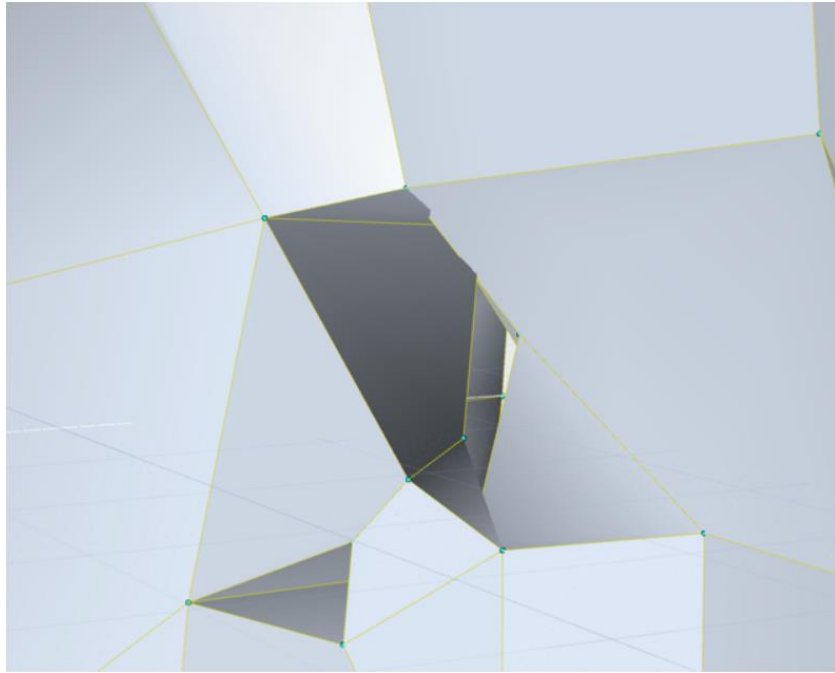
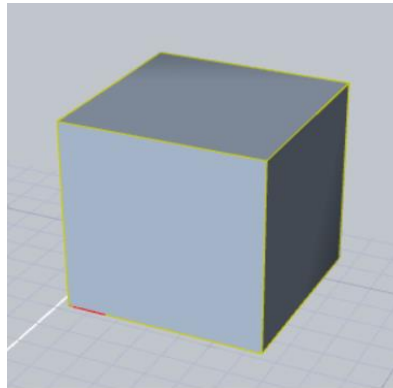


Figure 18: Overlapping and hidden faces

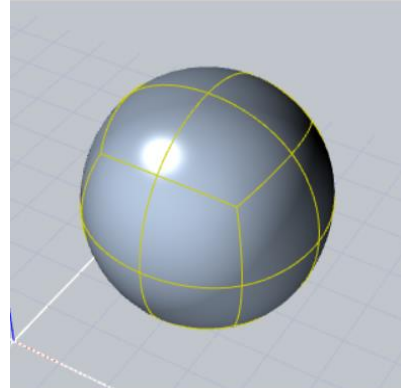
Another problem encountered while using this tool is merging the design and the non-design space and trimming the bottom surface. The most efficient way of solving this problem was by using EVOLVE software mentioned as it allows the user to manipulate the NURBS geometry using their vertices, faces and edges. Therefore, in this paper as a symmetrical model is being used, half of the section was created using INSPIRE tool and this section was later fine-tuned and mirrored using EVOLVE software.

3.2.4 Completing the NURBS model

NURBS curves and surfaces are used in EVOLVE for its 3D modeling [41]. Converting a polymesh to NURBS is done by selecting Nurbify on the control panel as shown in Figure 19.



(a)



(b)

Figure 19: (a) Polygonal cube and (b) Nurbified Polycube

Once the half section of the model is imported into this software the model was oriented such that the center is aligned with global XY axis, where the two white lines intersect as shown in Figure 20.

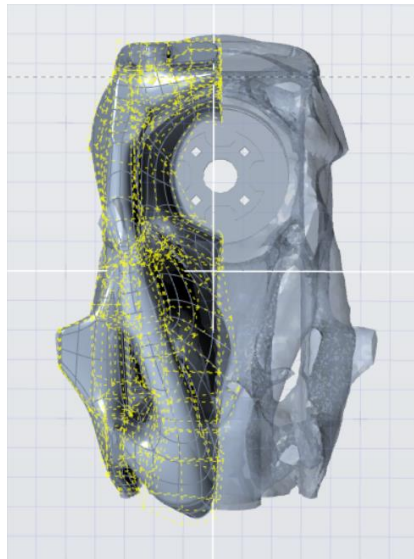


Figure 20: Aligning model with the global axis

An efficient mirror along the XY axis can be achieved by aligning the center vertices of the half model along the white lines, the EVOLVE software automatically welds the vertices that are coincident as shown in Figure 21.

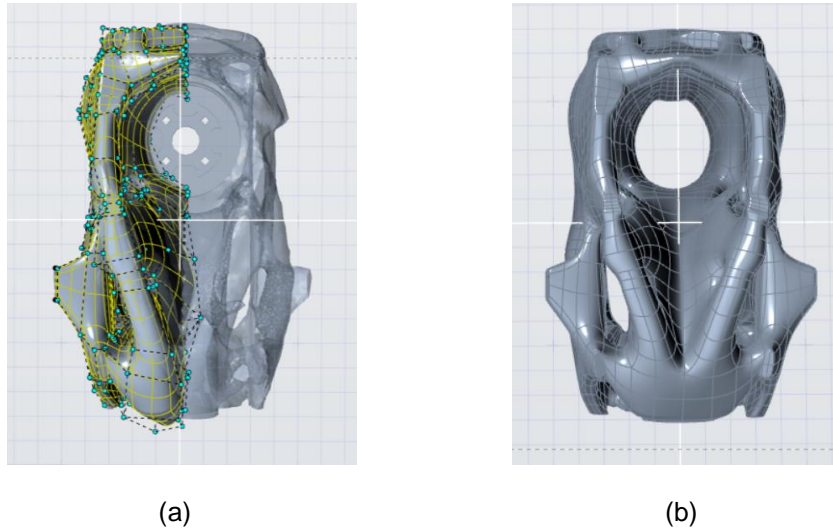


Figure 21: (a) Aligning vertices to center line and (b) mirroring the NURBS

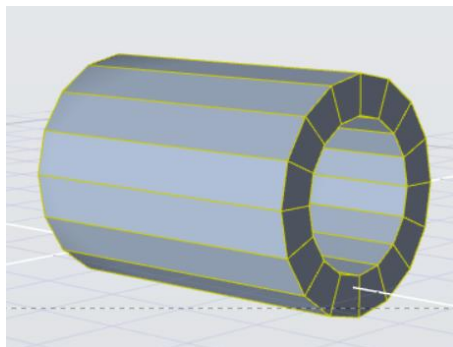


Figure 22: Creating a cylinder using PolyDisk feature

As the cylinder in the rod and mount interface was difficult to fuse with the design space, a simple cylinder using the PolyDisk tool was created and the faces were extruded to the required length as shown in Figure 22. The next step is to combine this PolyDisk with the design space to edit the faces using the combine feature shown in the Figure 23 which is under the transformation tools. A few faces on the cylinder were modified/deleted and the edges to the design space were bridged thus creating one complete design as seen in Figures 24 and 25(a).

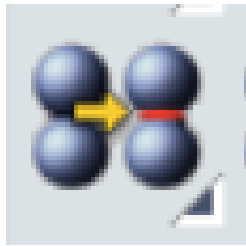
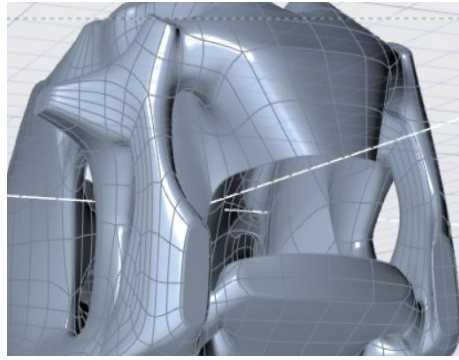
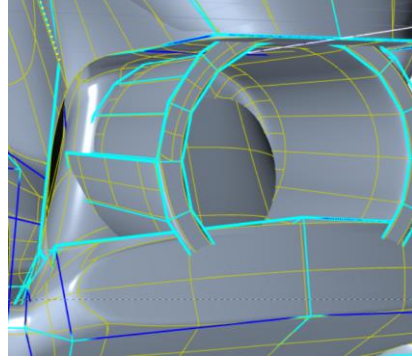


Figure 23: Combine feature

Creating one complete design is always better than combining design and non-design spaces because the combining points become weak areas. After combining the non-design spaces with the design space, the bottom surface and the circular cut out was trimmed as shown in Figure 25(b). While creating a NURBS model it is important to remember that 4 sided faces are the best to work with and to make the faces as big as possible. Too many edge loops should be avoided. Next the tolerance check tool under the analyze group should be used to make sure the PolyNURBS created using this software is a closed solid, and if not fix it before it gets too complex. Lastly before importing the part as an STL file to build the lattice structures use the NURBS to Polymesh tool under PolyNURBS tool to create a polymesh object which can also be imported directly as an STL file to 3D print.

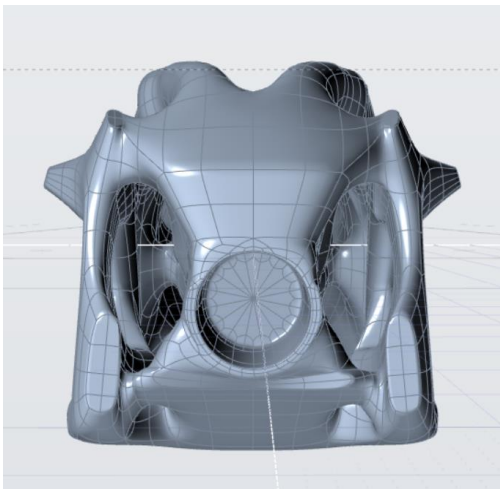


(a)

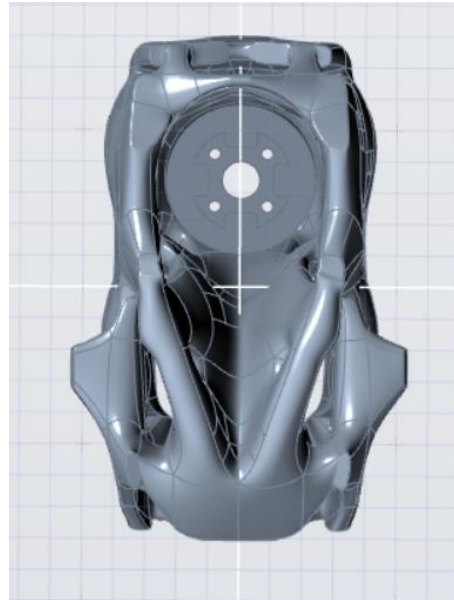


(b)

Figure 24: (a) Deleting a few faces in design region, (b) Deleting faces on the non-design region



(a)



(b)

Figure 25: (a) Combining the design and non-design region, (b) Final NURBS model

3.3 Lattice Optimization

This topic gives a brief introduction to the lattice generating tool Element Pro, a software developed by nTopology for performing lattice optimization. The steps taken to perform the optimization are discussed in detail. Displacement analysis is performed on the unthickened lattice structures using OptiStruct.

3.3.1 Tool used for generating the lattice structures

Element Pro is a professional structure design and optimization software created by nTopology for demanding applications. Traditional surface modeling tools are used to create the initial object. The design is then imported into Element, where the user performs generative design through functional modeling. [42] Element has several predetermined functions that the user can manipulate depending on a given application. Users can also create their own functions through the user-friendly Rule Builder tool.

3.3.2 Lattice Optimization objective and process

Lattice optimization helps in building lightweight structures with increased stiffness. The objective to perform lattice optimization in this paper is to create a model which has high stiffness and strength while reducing or maintaining the mass of the model. The process for building these lattice structures is explained below.

The aim is to build lattice structures inside the NURBS model which was created earlier. While creating a polymesh object, it is possible to change the surface mesh dimensions to get the required mesh size. One of the problems encountered here was that a uniform mesh was not created in the entire structure even after specifying the minimum and maximum dimensions in tool used as shown in Figure 26. The solution to this problem

was to import the STL file into the lattice generating tool to remesh and refine the mesh of the model and thus create a uniform smooth mesh throughout the structure. But due to limitations in the software used to create these lattice structures higher values of mesh size resulted in change in the geometry of the model which is not desired as shown in Figure 27.

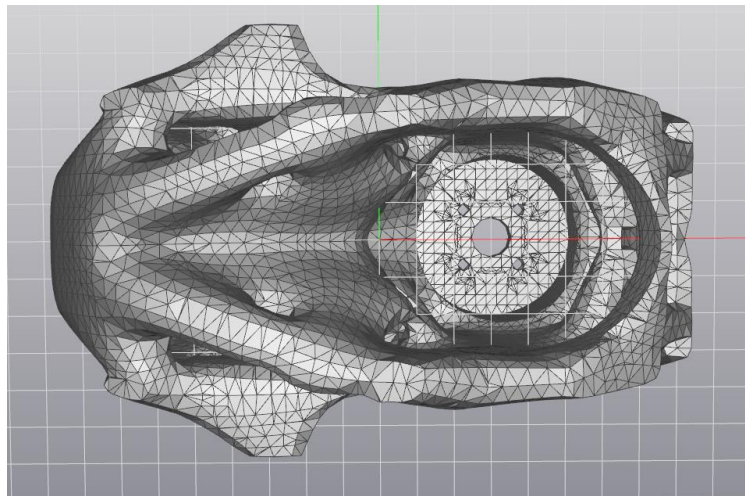
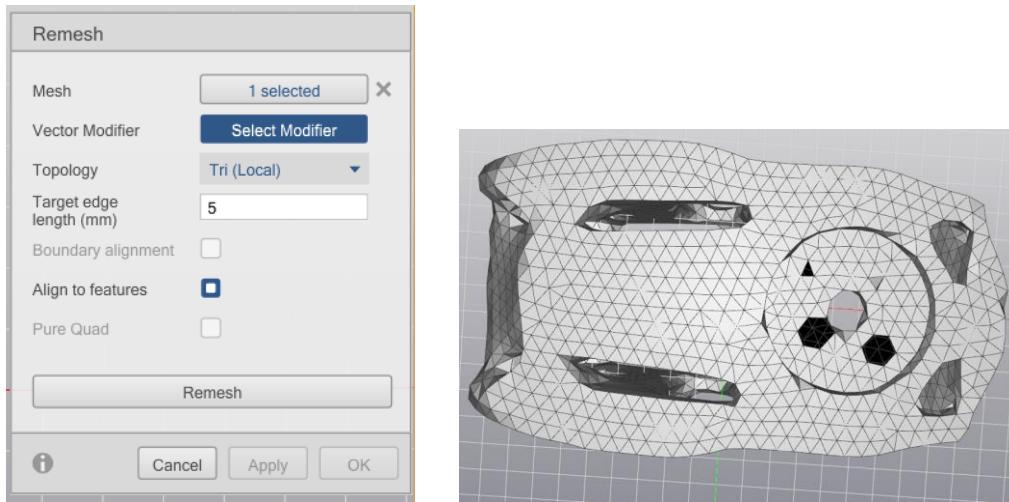


Figure 26: Model imported with a nonuniform mesh size

The higher the target edge length is specified more errors are created in the model. Due to this reason the surface lattice size and the internal volume lattice is not the same.



(a)

(b)

Figure 27: (a) Remesh tool (b) Remesh result will unwanted holes

3.3.3 Defining the lattice rule and building the lattice structures

Defining a lattice structure is based on the property that is required of these structures. Since the objective is to build lattice structures such that stiffness of the model is increased it is preferable that tetrahedral lattice structures are created. Element Pro provides an option to the user to select the lattice structures from a wide variety of predefined tessellations and units or to create their own structure from scratch [43] Using the Ruler Builder tool, a tetrahedral lattice structure was created as shown in Figure 28.

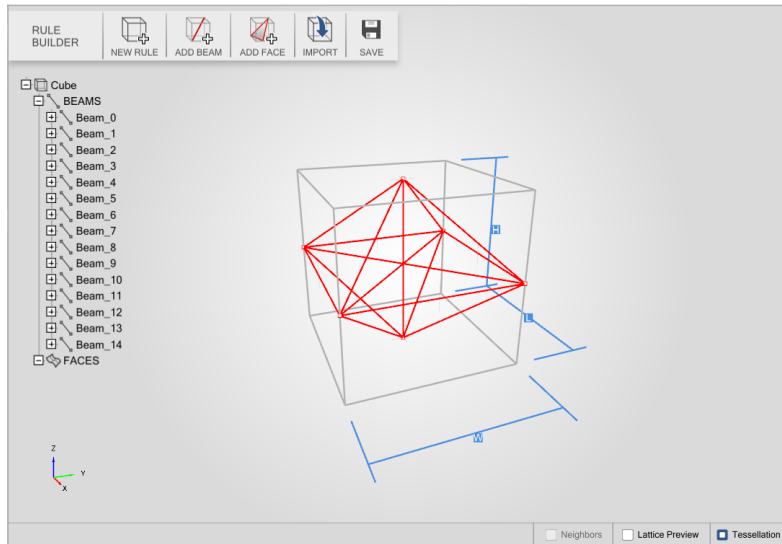


Figure 28: Tetrahedral lattice structure

After defining the lattice structure, the next step was to create a surface lattice on the part with edge length of 5mm as shown in Figure 29.

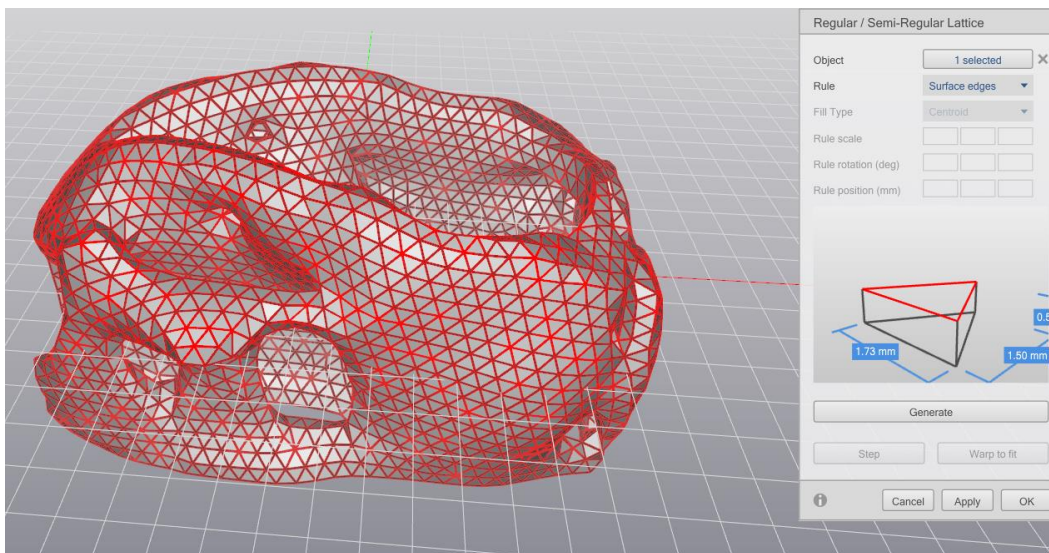


Figure 29: Surface Lattice

Using the new lattice rule, the volume lattice was created as shown in the Figure 30 and trimmed so that only the members inside the meshed geometry exists. The attractor tool was used to attract the volume lattice to the surface lattice to then later merge the two lattices together and clean up any open beams which are remaining. The lattice members a uniform thickness of 1.5mm as shown in Figure 31. To perform further analysis on these lattice structures the file was saved as an LTCX file and with the help of an Abaqus CAE script provided by nTopology converted it into an INP file which can be imported into HyperMesh for displacement analysis

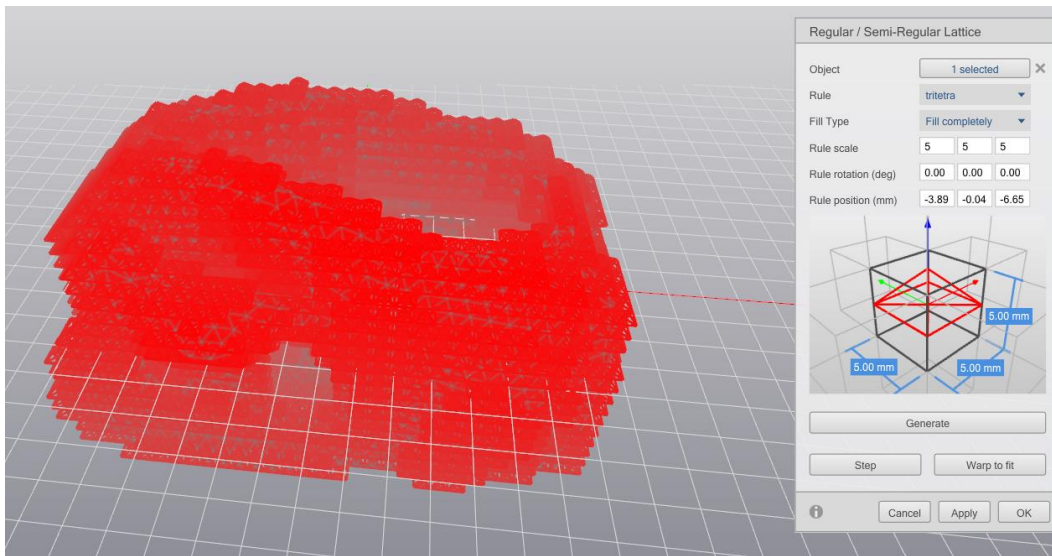


Figure 30: Volume Lattice

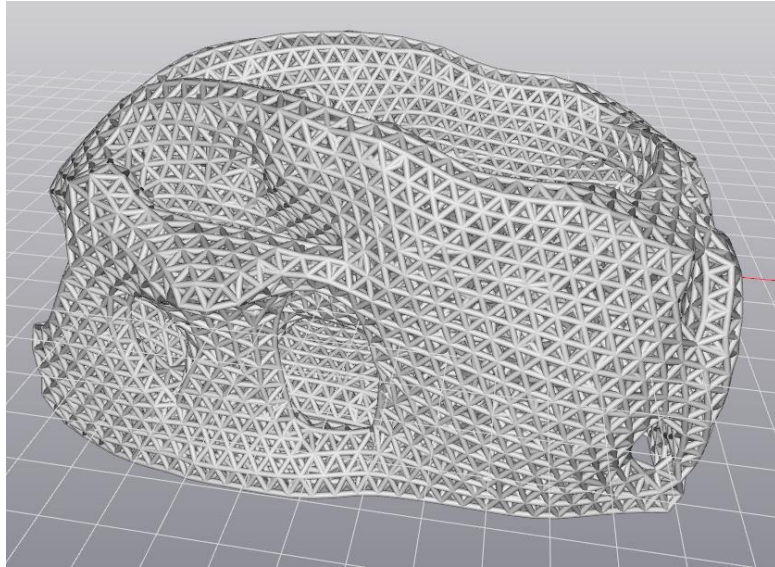


Figure 31: Thickened Lattice members

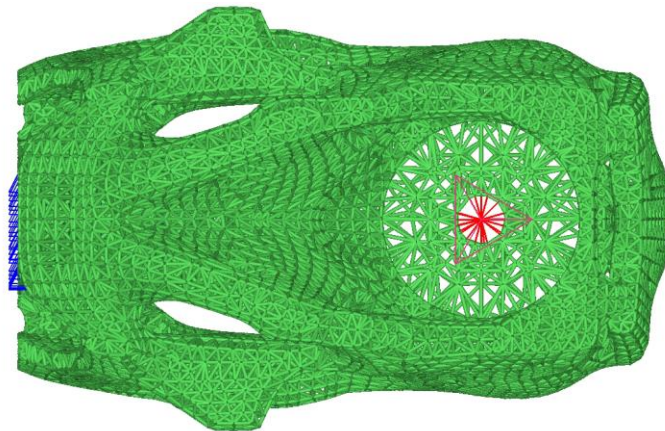
Chapter 4

Analysis and Results

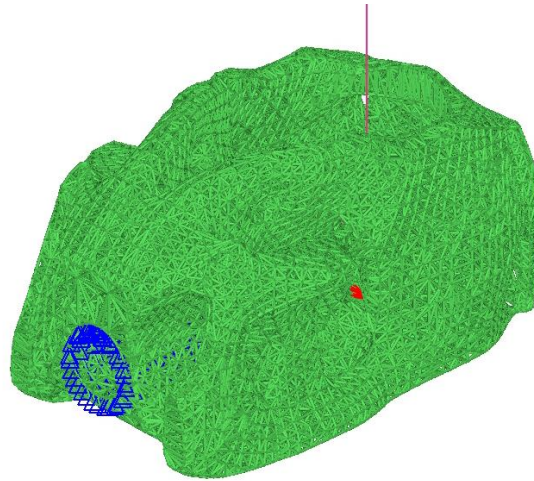
This chapter discusses the results of the displacement analysis and compares the displacement to the original base model shown in Figure 6.

4.1 Displacement Analysis and mass calculation

After creating the lattice structures, they need to be imported into an FE solver for performing linear static analysis. The lattice generating tool used here does not create a file type which is supported by the finite element tool used to run the analysis. Therefore, the lattice structures are imported as an LTCX file and an Abaqus CAE script is run to convert the LTCX file into an INP file type which is supported by the finite element tool. Rod elements need to be used as they support axial loads.



(a)



(b)

Figure 32: Rod Elements prior to displacement analysis (a) top view and (b) load acting downwards shown as a red line

The lattice structures imported should have their element configuration as rods and these rod elements are given a certain diameter. Material and property is assigned to all the elements and a force of 17lbs is applied as shown in Figure 32. The component is fixed at the mount and rod interface. Once the analysis is run the displacement for a particular point is noted down. Linear static analysis for a beam section of 0.5 mm, 0.75 mm and 1 mm radius is performed and the displacement is noted down for each of these results and compared to the original base model. Mass for each of these dimensions is also calculated. The total mass of the component is calculated by selecting mass calculate under the tools feature in OptiStruct which directly calculates the mass of the selected component or elements.

4.2 Results

This section provides the results achieved for all the methodologies followed in this paper.

4.2.1 Topology Optimization results

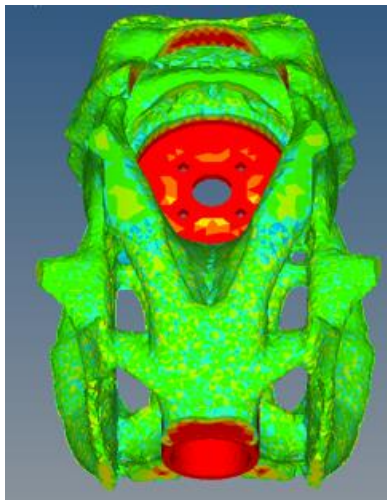


Figure 33: Topology Optimization result for 25% volume fraction

Figure 33 shows the result for topology optimization with 25% volume fraction and with minimum and maximum member size of 10 mm and 20 mm having a gap of 40 mm. The structure shows a uniform member size throughout and the part can be manufactured as there are no discontinuities in the elements. This result was the most suitable of all the other topology optimization results and was used to perform further analysis.

4.2.2 Geometric Modeling results

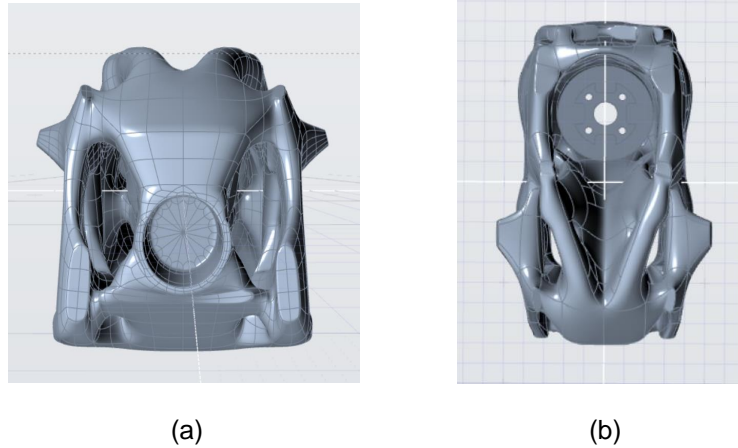


Figure 34: Final NURBS model (a) front view and (b) top view

The NURBS model as shown in Figure 34 has a smooth surface. These two images show how a smooth and organic shape can be created using NURBS by combining the design and non-design region.

4.2.3 Lattice optimization results

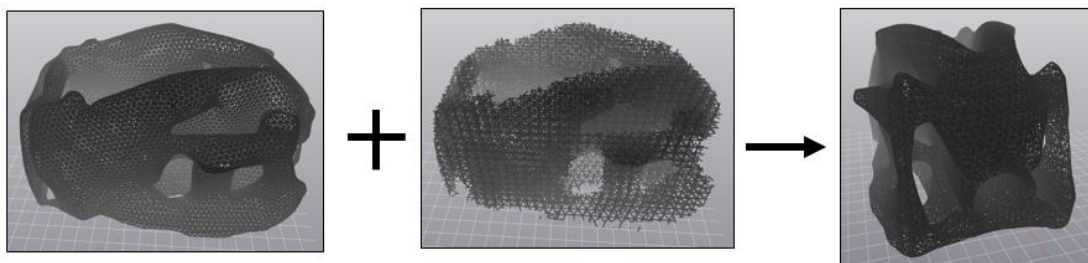


Figure 35: Lattice structures (a) Surface lattice, (b) Volume Lattice and (c) Merged lattice structures

Figure 35 shows the lattice structures created, the image (c) shows the merged lattice members, the member size of which can be varied as required. The unthickened lattice structures were imported into a finite element solver to calculate the displacement.

4.2.4 Displacement results

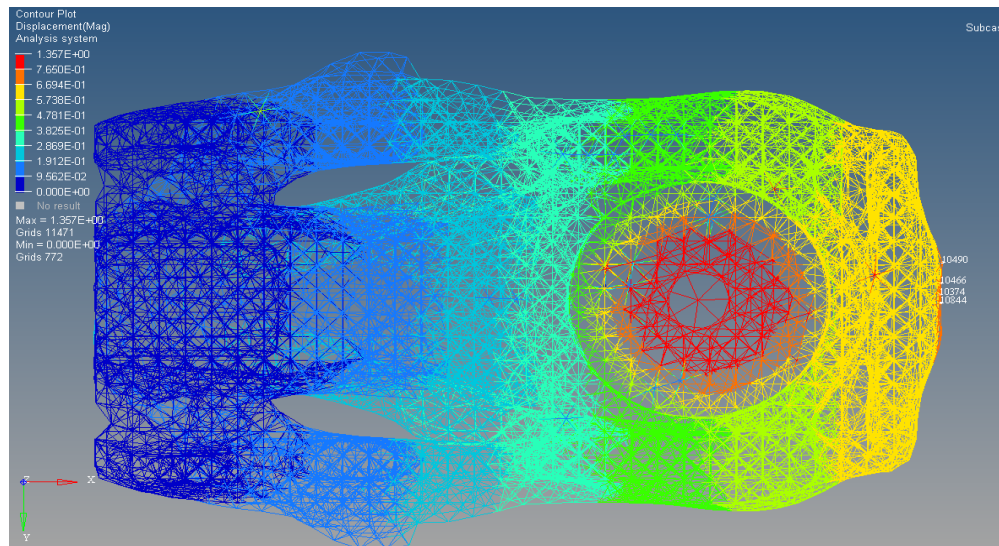


Figure 36: Displacement result for rod diameter of 1 mm

The point at the right end, opposite the mount rod interface is the the point taken for considering and comparing the displacement. Considering the rod diameter as 1mm the displacement at this point was calculated to be 0.675 mm as shown in Figure 36. Similarly for a rod diameter of 1.5mm and 2mm as shown in Figure 37 and 38, the displacement was calculated to be 0.35mm and 0.2 mm respectively. The displacement went on reducing as the thickness of the structures was increased but this resulted in an increase in the total mass of the component.

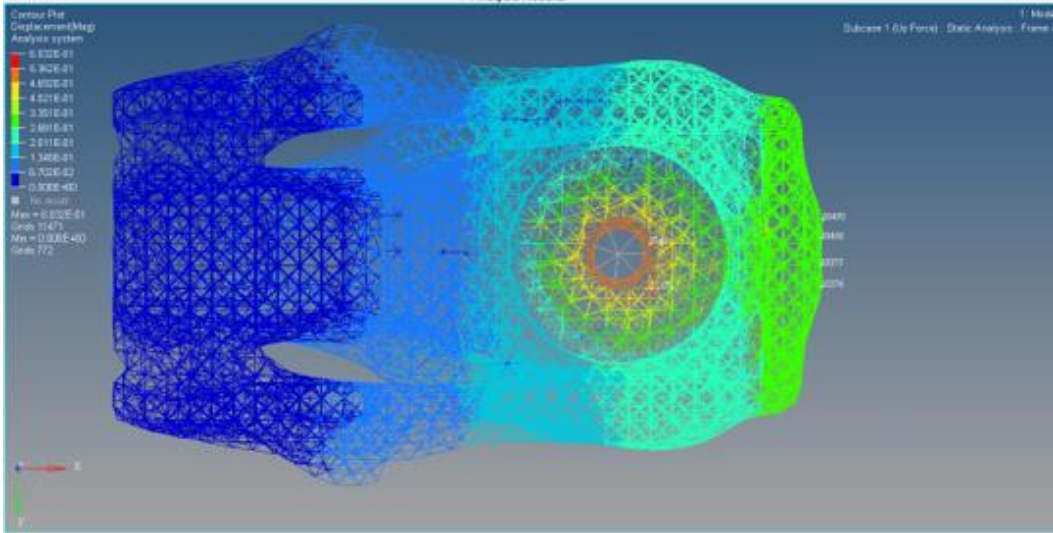


Figure 37: Displacement result for rod diameter of 1.5 mm

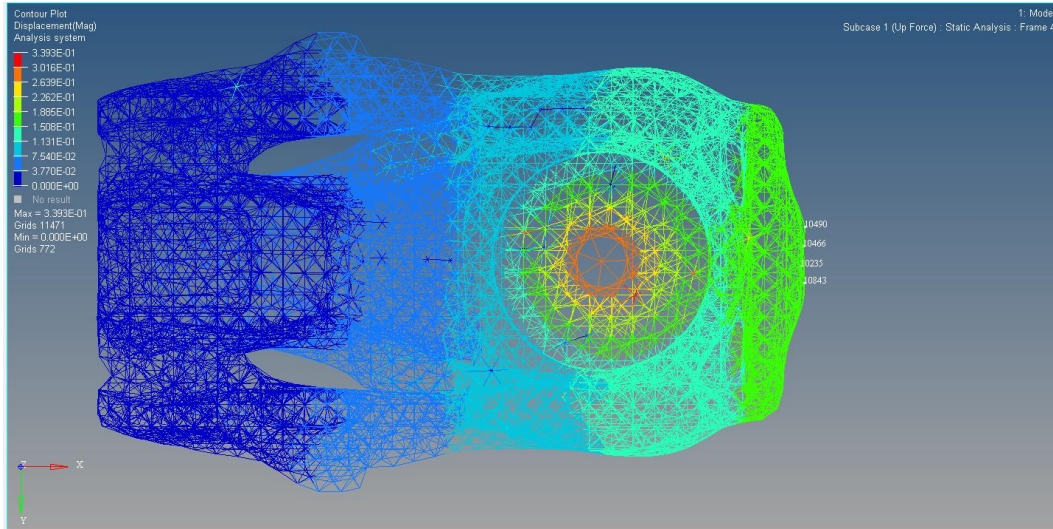


Figure 38: Displacement result for rod diameter of 2 mm

4.2.5 Mass and displacement comparison with baseline model

Table 1 summarizes the results for the total mass and displacement calculated compared to the baseline model. The value for the baseline model was taken from [44] where a design methodology for continuous carbon fiber is used to manufacture the part. Inaccuracy of the geometric parameters while performing the topology optimization in this research led the total mass of the optimized component to be extremely high and therefore this result is not a valid numerical comparison to the baseline model.

	Baseline model	Optimized model		
		Rod Diameter 1mm	Rod Diameter 1.5mm	Rod Diameter 2mm
Weight (gm)	57	224	505.5	898.67
Displacement (mm)	0.77	0.675	0.35	0.2

Table 1: Mass and displacement comparison

Chapter 5

Conclusion and Future work

In this research effort a detailed methodology for topology and lattice optimization has been presented. The focus here was to reduce the total mass and displacement of the component compared to the original design by exploiting all the advantages that additive manufacturing provides. The topology optimization process provides the best material layout for a given volume fraction constraint subjected to minimizing the compliance. NURBS surfaces allowed for a smooth geometric interpretation of the topology optimized result which is actually manufacturable. The tetrahedral lattice structures impart strength to the component resulting in a lightweight stiff structure.

In this instance the geometric parameters of the model that was optimized were inconsistent with the actual model used for comparative study. This led to miscalculations in the topology optimization thereby considerably increasing the mass of the optimized component. Due to this, a numerical comparison between the optimized result and the original part is not available. Also, the lattice generating software is currently limited in its functionality, in that it could not create a uniform mesh throughout the component for a larger mesh edge length. However, theoretically with the correct geometry and the available computational power, the methodology presented would result in a stiffer part of equal or lesser total mass.

Future work towards this research goal would be to re-run the entire optimization with the real world geometric parameters for the concerned part and provide a basis for comparison. Experimentally validate the above by 3D printing the lattice optimized part and determine the physical properties empirically. In the long term it becomes necessary to

understand how a change in geometry of part would affect the optimization procedure. This determination would allow for a widespread implementation of the stated methodology.

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Biographical Information

Nagadurga Srinivas Sripada received her Bachelor of Engineering (B.E) degree in Mechanical Engineering from Mumbai University, Mumbai, Maharashtra, India. She joined the Department of Mechanical and Aerospace Engineering at The University of Texas at Arlington in August 2015 as a graduate student and earned her Master of Science degree in Mechanical Engineering in December 2017.