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Parametric 3D-fitted frames for packaging heritage artefacts

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Abstract

Packing fragile heritage artefacts is a challenge almost all heritage organisations have to deal with when faced with the task of transporting or storing the artefacts. The packaging solution requires fitting the artefact correctly in order to ensure the protection and safety of the item; but also to be easy and cost effective to produce. Different techniques have been traditionally used, such as double boxing, padding negative spaces and cushioning braces. However, the introduction of 3D technologies for documenting these artefacts enables innovative uses of this data for packaging purposes. Hence, this paper proposes the use of the generative modelling language in order to produce unique 3D-fitted containers for packaging heritage artefacts which fit tightly the artefact, and can be made to be reusable and more durable than traditional packaging solutions. We propose to adopt an octet lattice as a low density internal structure to the proposed container. By combining the parametric package design, 3D meshes acquisition and 3D printing techniques, we present a technology based solution to the traditional problem of protecting these valuable artefacts for transportation and/or storing purposes.

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Picture/Image Generation—Line and curve generation I.3.5 [Computer Graphics]: Computational Geometry and Object Modeling—Geometric algorithms, languages, and systems J.6 [Computer Applications]: Computer Aided Engineering—Computer-aided design (CAD)

1. Introduction

Almost all heritage organisations are faced with the task of planning and designing packaging solutions when they need to store or transport artefacts to other locations. Packaging heritage artefacts is a complex issue where one solution does not work for all situations, due to the different physical characteristics of these artefacts. However, most packaging solutions need to address a basic set of requirements. These include fitting the artefact correctly; supporting its weight effectively; minimising the amount of handling an artefact requires and simplifying the unpacking and repacking. Furthermore, more complex shapes and fragile items require additional protection to mitigate the effects of temperature, humidity and vibration; as well as appropriate spacing of artefacts if they are being grouped for transportation. As such, different techniques are commonly used by heritage technicians as described by [Bau93]. But the task is still very much a craft skill. Automating the creation of packing artefacts could both save money and time, and additionally offer a solution to smaller and less skilled users, or less well funded institutions, as well as an efficient means of creating packing.

The increasing popularity of 3D documentation of heritage artefacts offers an opportunity in the packaging field. This is because accurate 3D models of artefacts can be used to automatically produce packaging solutions in an easier and less time consuming manner. As such, this paper proposes the use of the generative modelling technology to automatically produce unique structures which can parametrically adapt to the size and the shape of a specific artefact. Combined with 3D printing techniques, this solution represents several advantages pver more traditional methods, such as the automation and ease of production as well as the reduction of material wastage.

The paper will be structured as follows. Section 2 will describe previous work on traditional methods for packaging heritage artefacts. Section 3 will describe and review the

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concept of low density structures and 3D printing. In section 4 and 5 we propose our 3D low density structure and describe its implementation, which takes advantage of generative modelling technologies. Finally, in section 6, we present our prototype, followed by some conclusions and further work.

2. Packaging heritage artefacts

Several solutions for packing heritage artefacts have been proposed within museum communities. Proper packing techniques are critical to ensure artefacts are stored and transported safely. In contrast, an artefact packed incorrectly can be permanently damaged. Another complexity is that each artefact requires a unique packaging solution. Hence, traditional methods for designing and producing packing might require several hours or even days to complete, depending on the specific case. In addition, different considerations need to be made for selecting the most suitable method for packaging a fragile and valuable heritage artefact. This includes the material, weight, stiffness and the shape of the artefact.

Packing materials are diverse and can have different effects on the artefacts. For instance, fragile artefacts made of material such as glass, charcoal or corroded metals are vulnerable to damage from abrasion; polished metals, varnished woods, oriental lacquer and other smooth-surfaced artefacts are vulnerable to imprints from plastic bubble wrap and foams.

Different shapes, weight and stiffness pose specific challenges to the packaging solution. While the main goal is to protect the artefact from potential damage during storage or transportation, another important objective of this proposal is to minimize the material usage, the size and the final weight of the solution. This will have a direct impact on the cost.

There are a variety of techniques that are traditionally used. These rely mostly on using cushioning materials in order to absorb shock, vibration and buffer the humidity. They include materials such as foam products that can be used in a variety of cushioning techniques. As described in [U.S99], these techniques include:

- **Cavity packaging**: This simple technique involves placing the artefact into a cut made in polyethylene foam with the shape of the artefact. This method is clean and easy to use for repacking (see figure 1-a).
- **Sparse layered packaging**: This technique is similar to cavity packaging, but the cushioning material is distributed sparsely around the artefact (see figure 1-b).
- **Double boxing**: This technique involves packing an artefact using two sequential boxes in order to cushion the artefact. For this, the artefact is cushioned inside one box. Then, another box at least 5 cm larger on all sides is used with further cushioning in between.
- **Padding negative spaces**: This technique involves packaging an artefact surrounded with tissue paper and then wrapping in successive layers of bubble wrap. The artefact is placed inside a container and then tissue or some other cushioning material is used to fill in the excess area.
- **Cushioning braces**: This technique involves using a cushioning bracket to hold the artefact in place.

Figure 1: *Examples of packaging techniques: (left) cavity packaging and (right) sparse layered packaging. ©Fenimore Art Museum and Darla Jackson sculpture blog*

These techniques demonstrate how the shape of the artefact plays a critical role in the production of the packing solution. Carving or designing a package around a shape is still a laborious process mostly done manually.

The advent of 3D technologies for the routine documentation of artefacts in collections (see [KREP*12]) represents an opportunity to use this data for packaging purposes. Reciprocally, the opportunity to enhance packaging techniques may motivate the adoption of 3D technologies for documenting, as information on the shape of the artefact can support different kinds of applications. The digital 3D shape of the artefact enables a completely automatic design and production pipeline of the 3D-fitted container for the artefact. The next section will introduce different types of structures which might be suitable for the internal structure of the packaging solution which will be 3D printed.

3. Low density structures and 3D printing

Low density structures are frequently found in nature and are widely studied in engineering, architecture as well as in product design. They are used as efficient structures that serve a variety of purposes ranging from bridges and roofs to internal structures of car seats, or toys.

One benefit of low density structures is that they reduce the amount of construction material required. Hence, reducing costs and/or final weight of the whole structure, while guaranteeing some mechanical properties that are desired for the product. Today, low density structures also inspire projects that are environmentally sustainable, since by minimizing material usage there is a reduction of waste. The potential to produce more durable and reusable packaging solutions is also an advantage.

Figure 2: *Two low density structures can be observed in the figure: (left) an example of a truss used in a bridge, and (right) an example of a honeycombed structure found in the Durvillaea antarctica alga (©Andre-Philippe Drapeau Picard)*

An example of these type of structures are trusses, which are illustrated in Figure 2-left. These are well known in architecture and engineering [Gor03]. In the language of structural engineering, a *lattice truss* or *space frame* is a connected network of struts, pin-joined or rigidly bonded at their connections. The purpose of such frames is to create stiff, strong, load-bearing structures while minimizing material usage. The mechanical properties of trusses have been widely studied and plenty of references are available, as well as software that deals with the calculations [CF12].

Other examples of low density structures can also be found in nature, where efficient structures with a reduced amount of material can be frequently observed. For example, Figure 2-right illustrates a transversal cut of the leaf of a alga specimen, showing the air-filled honeycomb structures that provides its buoyancy.

Moreover, internal structures referred to as *cellular materials* can be found within bones as well as in honeycombs and are famous for their exceptional mechanical properties and for their light weight. [Chr00] provides a detailed survey on this type of structure. Cellular materials are also known as *lattice-structured materials* or *cellular solids*. They are characterized by their relative density, and are a hot topic of research nowadays because of their wide range of industrial applications.

In product design, honeycomb inspired structures brought innovation to aircraft design, motor vehicle technology as well as to light-weight construction. They have also formed the basis for the development of honeycomb structured panels [Bit97, Wad06].

The application of low density structures as a solution for designing internal structures have gained prominence with the advent of *3D printing* or *rapid prototyping*. 3D printing is a manufacturing approach that can theoretically build any three-dimensional shapes and topologies by different mechanisms. The most popular is known as *additive manufacturing*, which produces a 3D shape by adding materials layer by layer [GRS09].

The range of base materials that are used in 3D printing is wide. The study of 3D printed object's mechanical properties with varying materials is still a topic of research. Thus, the structural analysis of 3D designs can suffer from the lack of information. In this work we are not going to explore the possibilities in varying the base materials or studying in detail their structural properties.

The recent improvements in the strength and durability of the base materials that are used in additive manufacturing has expanded the range of its applications. Therefore, additive manufacturing is bringing a great change to different types of industries, including the packaging industry.

In this paper we propose a solution for printing a 3D fitted container for packaging heritage artefacts. We argue that the internal structure of the fitted frame should be designed using low density structures to benefit from its advantages. Several projects in product design that take advantage of such internal structures along with 3D printing techniques are being proposed [A. 12]. There is also commercial software available, for instance, the Selective Space Structures (3S) Software from Netfabb [Net12], which is a high-end design tool that allows the development of complex unit cell structures for additive manufacturing purposes. Several mesh generation tools are available as well. The following section will introduce the proposed structure before discussing its implementation.

4. Proposed low density structure for packaging heritage artefacts

Inspired by the evidence shown in section 3, we propose to model the internal structure of our 3D-fitted packaging solution as a low density structure. In order to design the container's internal structures, we looked for ways to fill the space with such sparse structures that could be efficient from the structural perspective.

In computer graphics literature, these structures - which are widely studied - are referred to as 3D meshes. In particular, the 3D meshes adopted for the finite elements methods (FEM) are directly related to the solution that we are looking for. When considering the adoption of FEM 3D meshing algorithms, we have to bear in mind that they are intended for FEM calculations and are built to produce virtual meshes. Thus, the mechanical properties of the mesh itself are not relevant to that field of application. In our case, after generating the 3D mesh wire-frame model we will need to process it in order to turn it into a 3D mesh surface, aiming to achieve a 3D printable truss. That is essentially the 3D mesh wire-frame model with thickness attributed to its edges.

There is a lot of commercial and open-source meshing software available. A review of these methods and software is beyond the scope of the present paper. A survey of 3D meshing software by Owen [Owe98], from 1998, is a review of the fundamental algorithms then available for 3D mesh generation. Owen's survey classifies the 3D mesh generators into two broad classes, that are structured and unstructured 3D meshes. The classification is made based on the criteria of interior nodes element's adjacency. Structured meshes have an equal number of adjacent elements, while unstructured meshes relax the node valence requirement, allowing any number of elements to meet at a single node.

More recently, FEM simulations in medicine, molecular biology and engineering have increased the need for quality 3D meshes. For instance, Zhang et al. [ZBS05] propose an algorithm and make an extensive comparison with other tetrahedral extraction methods from imaging data.

We have adopted the branch of structured 3D meshes as they are more stable from the mechanical point of view. In [Wad06], Wadley highlights the strength of such structures within the context of industrial applications. One interesting subset of structured 3D meshes are the space-filling polyhedrons [Cox73, Cri73].

A space-filling polyhedron is a type of polyhedron which can be used to generate a tessellation of space. The cube is the only *platonic solid* possessing this property, and its tessellation is widely adopted in computer graphics, the classic Octree data structure and the Marching Cubes algorithm explore this basic tessellation of space. However, other combinations of polyhedrons can also be used to fill the space.

A specific configuration of octahedron and tetrahedron do fill the space. Figure 3 illustrates the octahedron frame (left) and a diagram that shows an exploded view of the octahedron and tetrahedron filling-space configuration (right). Other options of space filling structures are available in the literature [FH99, CJT11]. Additionally, topological interlocking of platonic solids [DEKBP03, EDP11] are also considered to have very good mechanical properties.

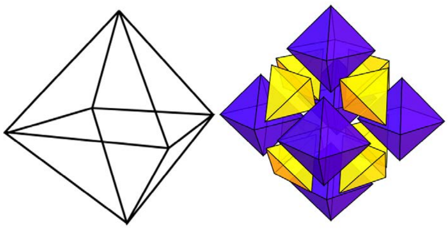

Figure 3: *Octahedron tetrahedron basic unit*

The octahedron tetrahedron filling-space configuration is known in the architecture domain as the *octet truss*. This structure is well described by Grosso et al. in [GG00] and its mechanical properties have been studied by Deshpande et al. in [DFA01]. The authors submited a prototype of the *octet truss* made of aluminium to a sequence of tests, as well as their theoretical values which are predicted by means of finite elements calculations. The authors concluded that the stiffness and strength of the *octet truss* material compares favourably with the corresponding properties of metallic foams, and that its high strength-to-weight ratio, relative ease of manufacture and potential for multi-functional applications makes it an attractive alternative to metallic foams. Thus, we suggest that the *octet truss* is a good starting point for the internal structure of our packaging solution. The implementation of this solution will be described in the next section.

5. Implementation using generative modelling

Generating an *octet truss* which fits tightly to the shape of an artefact presents different challenges. The truss needs to be easily adaptable to fit any 3D model which needs to be packaged, despite its shape and size. In addition, two operations need to be taken into account. The first is defining the empty space in the centre where the artefact is going to fit. Secondly, the truss needs to be cut in half or in more pieces if there are undercuts or recessed surfaces in the artefact, in order to allow the artefact to be placed and released from the structure.

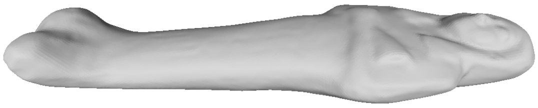

Figure 4: *Example mesh for producing a suitable octet truss for packaging*

Before building the *octet truss*, it is necessary to have information on the 3D shape of the artefact. For this, a 3D model with a low level of detail can be used as accuracy is not a critical issue. This is especially the case if the artefact still requires cloth or other wrapping to protect its surface. This might be particularly useful for artefacts which are not completely rigid or are very fragile. Hence cost effective techniques, such as photogrammetry ([VG06] and [Aut12]) are possible for many artefacts. For demonstration purposes, we used a delicate artefact (shown in Figure-4) which 3D shape data was acquired using a 3D scanner. The 3D mesh was post-processed and simplified using the Meshlab tool [Mes12] by using a Poisson surface reconstruction.

In order to address the challenges previously described, we considered using a combination of a mesh generation or grid generation tool with a modelling package for defining the empty space. For this, different public and commercial mesh generation tools are available. Schneiders presents a comprehensive list of examples of these systems [Sch12]. Nevertheless, these are focused on producing mainly wireframes or grid structures. In addition, the use of modelling packages introduces many complexities to the construction of the truss and requires manual intervention each time a new solution is created. Instead, we required an integrated modelling solution which could produce a mesh using the octahedron tetrahedron configuration as the basic unit. But most importantly that produced a printable *octet truss* and not only a wireframe.

We found a suitable solution by using the generative modelling language (GML) [Hav05]. This tool allowed us to define the sequence of processing steps to build the *octet truss* by working with a wireframe which is converted into a truss at the end of the process. It also allowed us to parameterise its construction. As such, a GML script was developed which can be easily adapted and configured for different types of objects using a set of parameters. These parameters include the number of units which will determine the width, height and depth of the *octet truss*, as well as for the cross section the radius of the prism and the number of edges (e.g. 3 makes a triangular prism while 20 approximates a cylinder).

The simplest approach for implementing the solution is by building a basic octahedron tetrahedron unit in wireframe and repeating this in a loop in order to create a box with a specified width, length and depth. This approach was initially tested, but it proved problematic once the artefact had to be fitted inside. This is because a further implementation of a Boolean operation algorithm needs to be implemented for generating the empty space where the artefact is going to be placed. Hence, the problem with this approach is twofold:

- It is difficult to decide whether the edge of a specific basic unit is within the artefact.
- It is difficult to decide which segment of the edge is outside the artefact if there is an intersection.

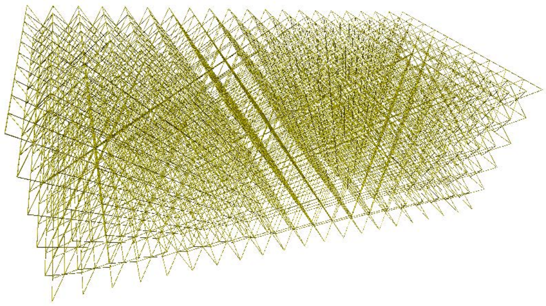

Figure 5: *Initial wireframe produced by using rays*

Instead, a better approach is to consider the whole frame composed of various lines or rays, rather than the individual basic units. Then, the 3D shape of the artefact can be used along with the ray-casting technique in order to determine where the rays intersect with the 3D mesh.

Using this strategy, the frame is first constructed in GML by using rays that travel from each face on the frame bounding box to its interior. Each face contains a list of vertices that define a tetrahedron. These rays need to travel in the directions of the edges connected to that vertex. These rays will always be outside the artefact and attached to the edge of the bounding frame. This approach also optimizes the frame structure as it minimizes the number of lines and therefore minimizes the number of intersection tests that need to be done. Once this frame is created, this must be translated and scaled to enclose the artefact that is being intersected against it. The resulting frame in this step is shown in figure 5.

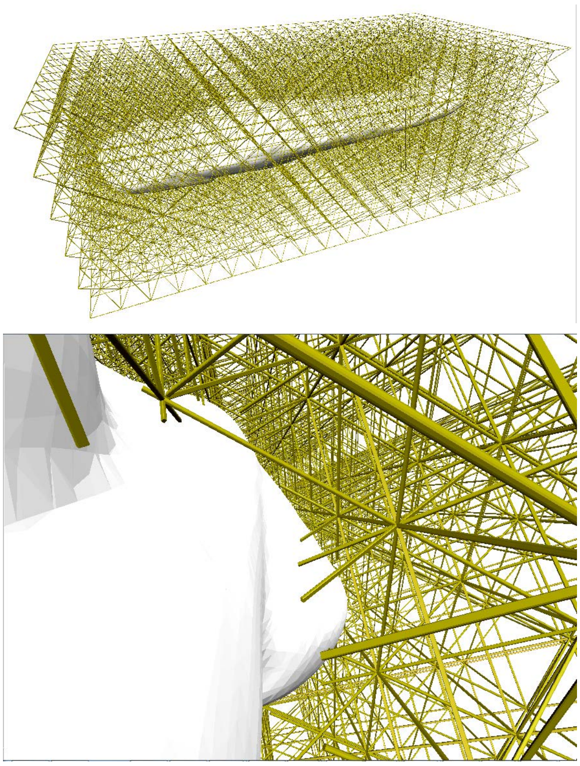

Figure 6: *Wireframe intersected with the 3D shape*

The next step is to convert the rays into a set of lines that are truncated to fit within the frame bounding box. These lines are then checked for intersection with the artefact. If there is an intersection the line is split in two leaving a gap where the artefact will fit tightly within the frame. Hence, the line is replaced by a line from its start point to the first point of intersection and a line from its end point to the last point of intersection (see figure 6-top). Additionally, the implementation erodes the lines that intersect the artefact so that there is enough space to place the physical artefact inside the frame once this is printed (see figure 6-bottom).

Finally, the frame is cut in half so that this can be opened and closed to place and release the artefact inside. For this, the lines are intersected against a plane that goes through the middle of the frame to produce two sets of lines. The final step is to convert all lines into prisms along the length of the line and create the 3D model which represents the *octet truss* for the two surface models (base and summit). These are the 3D models which will be printed as the final solution.

The final *octet truss* is shown in figure 7. As illustrated in the figure, this approach allows for fitting a shell case to protect further the artefact if this was required. This shell case can easily be developed in a modelling package by scaling the artefact, cutting it in half and shelling each side. Hence, the object has a double casing to further protect the heritage artefact during transportation.

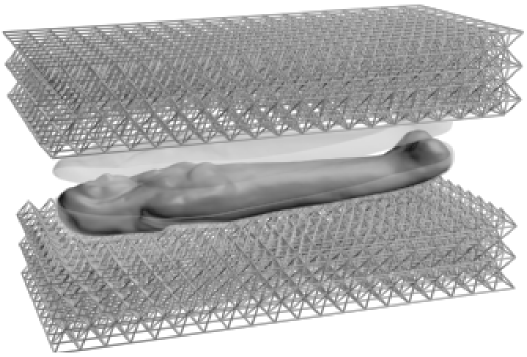

Figure 7: *Final octet truss ready for printing*

In order to verify the suitability of the approach and the script, we tested the script with a mixture of 3D shapes of fragile artefacts. These have been acquired with a variety of 3D acquisition technologies. Nevertheless, the steps to produce the *octet truss* are the same producing promising results so far. These results are illustrated in figure 8. The *octet truss* is feasible for different types of objects; although we did not tested undercuts.

6. 3D Printing the structure

As a proof of concept, we are in the process of finding the adequate density and thickness dimensions for printing the *octet truss* for a test artefact. We are experimenting with a Zcorp 510 machine using a plaster based powder (ZP150) to generate the structure layer by layer. This machine has several advantages to other 3D printing technologies. For instance, internal supports can be generated that are separate to the structure itself and so can be easily removed upon excavation of the structure; or that the porous powder can be infiltrated with epoxy resin to significantly increase the material strength.

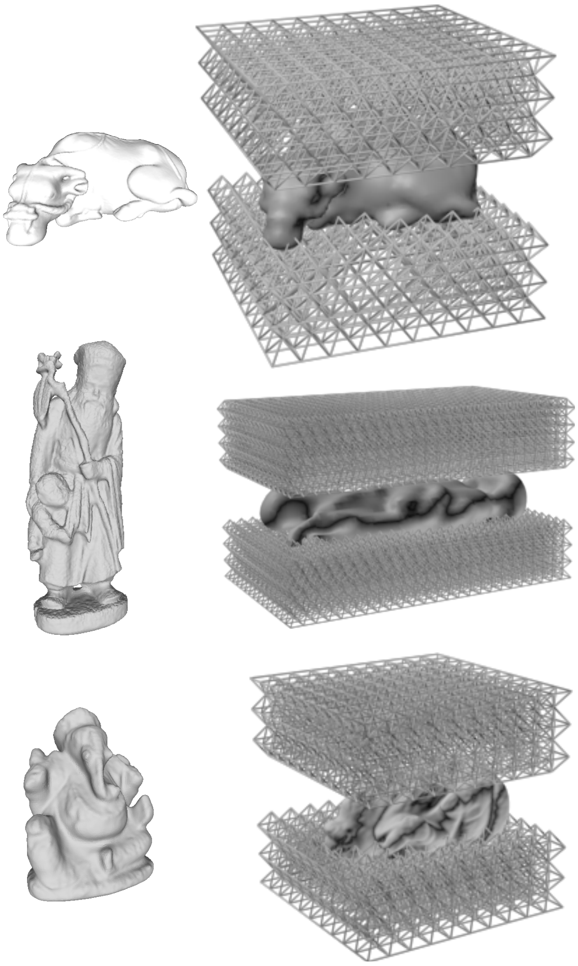

Figure 8: *Examples of different 3D shapes tested to produce an octet truss for packaging*

For an initial test, we have generated five different versions of the *octet truss* which are illustrated in figure 9. All of these were produced as a cube of 5 cm edge, with a thickness or diameter which varies 0.5 mm starting from 1 mm to 3 mm. By using the parametric implementation for the *octet truss* mesh generation, the density and the thickness variation is straightforward. The main objective of this test was to determine the optimal thickness which made the truss feasible to print in the Zcorp 510 technology. This was mainly motivated by a failed print which we previously attempted for an *octet truss* for a test object with a 1 mm thickness.

The test verified that using a 1 mm thickness is not feasible as it makes it difficult to remove the structure from the machine. This is illustrated by the broken edges on the thinner structure in figure 9. Nevertheless, structures with a thickness of 1.5 mm thickness seem to hold together and are feasible for printing as shown in figure 10.

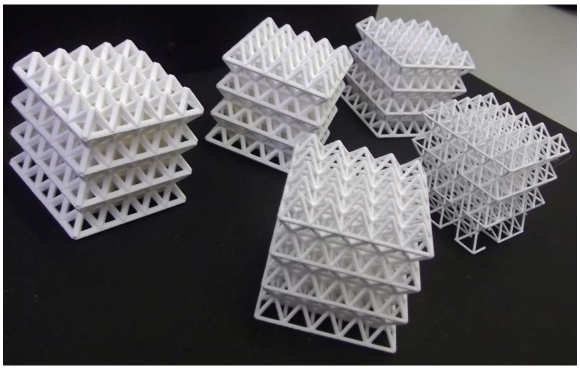

Figure 9: *3D printed octet truss with thickness varying from 1 mm to 3 mm*

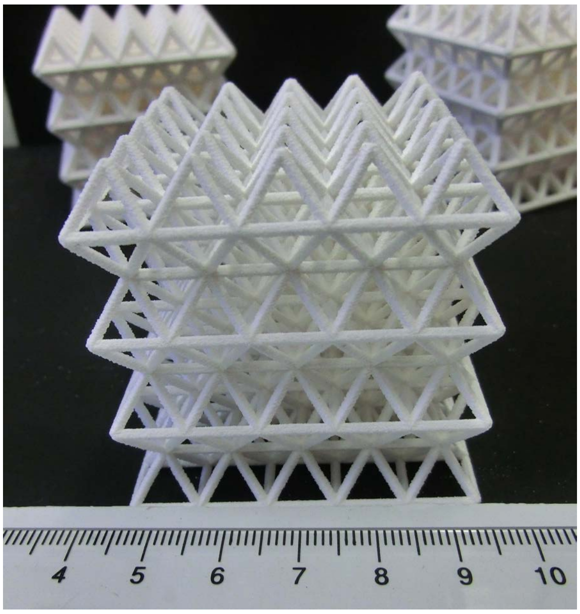

Figure 10: *3D printed prototype with 1.5 mm thickness in detail*

However, we still require of further testing to determine the optimal thickness so that the structure is not too fragile when placing the artefact inside it. For this, we have planned performing experiments involving testing the load capacity of the structures supporting a small fragile object. This will include both a compression load test case and a drop load test case.

Looking at practical issues, we observed that producing these structures took approximately 3 hours to print all of them in a batch. In addition, it took around 1 hour to excavate them and get them ready for infiltration. The time spent on infiltration might vary depending on the amount of epoxy resin which needs to be applied. Moreover, we made an analysis of the material usage and the cost of producing this type of solution. For this, table 6 provides information on the amount of material used and the costs associated with the material used for each printed structure. In addition, labour costs will require to be added in order to produce an overall cost.

Thickness	Percentage of volume filled	Mass	Material cost
1.0 mm	4.3%	7.7 g	£1.28
1.5 mm	9.7%	15.6 g	£2.59
2.0 mm	17.3%	25.6 g	£4.25
2.5 mm	27.1%	37.8 g	£6.28
3.0 mm	39.0%	51.8 g	£8.61

Table 1: *Values for the printed 5x5x5cm cube with different thickness: percentage of the total volume that is actually filled by the structure, as well as the respective mass and calculated costs for the given mass*

7. Conclusions

The movement of heritage artefacts is a process most heritage organisations need to undertake. Packaging artefacts correctly is critical because artefacts are at their most vulnerable when transported. Hence, this paper has introduced an innovative approach for packaging such artefacts based on 3D technology. The proposed solution makes use of an *octet truss*. This is produced using a generative modelling approach so that it can parametrically produce structures that will fit any artefact. The resulting structure provides a number of advantages:

- A bespoke packaging solution that is tailored to specific artefacts.
- An easier and more automatic process than traditional methods.
- Requires the 3D documentation of the artefact, which in turn can be used for different purposes (e.g. conservation, condition assessment).

Although, such a packaging solution might incur a higher cost to produce when compared to traditional methods, we estimate that this is balanced by the fact that less time needs to be spent producing the packaging.

Further work, beside the on-going printing and testing work, involves improving the proposed *octet truss* achieved so far. This can be achieved in different ways. One is to consider the production of a protective case for the object to be place in between the object and the *octet truss*. To do so, a possible approach would be to 3D print the protective case by means of off-setting the object mesh as proposed by Liu in [LW11], and then fit the protective case to the *octet truss*. Other issues include exploring the use of alternatives trusses, dynamically determining the cutting plane (to support undercuts) and considering the artefact weight to dynamically adapt the structure. The final goal is to minimize material needs, while guaranteeing that the package frame protects the artefact in transportation, and potentially storage, conditions.

In addition, further printing experiment with different materials may provide a strong and sturdy support for the object. Ideally the material in immediate contact with the object will be softer and more forgiving to the surface of the object and this can be achieved by either using a multiple density 3D printing machine (e.g. Objet Connex 500) or by manipulating the structural density surrounding the object such that thinner walled, less stiff structures can be used to surround the object. Similarly the overall density of the structure needs to be considered to optimise the weight of the structure whilst providing sufficient strength and stiffness to withstand load cases that are typical for stacking and transit. Although we could not explore the wide range of possibilities regarding the production of a prototype, we are convinced that the proposed structure is feasible and a rigorous exploration of the range of possibilities and technology limitations is left as future work.

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