

Digital workflow for creating 3D puzzles to engage audiences in the interpretation of archaeological artefacts

Karina Rodriguez Echavarria¹ and Myrsini Samaroudi¹

¹Centre for Secure, Intelligent and Usable Systems,
University of Brighton, UK



Figure 1: a) 3D scanned model of pottery urn artefact; b) 3D model of puzzle pieces of reconstructed urn; c) printed parts of the puzzle

Abstract

3D physical puzzles are typically used to engage audiences in the interpretation of archaeological artefacts in a museum exhibition. The reason for this is that a puzzle can be seen as a game but also as a complex activity that archaeologists undertake to re-assemble fragments. The contribution of this paper is a novel digital workflow for the design and fabrication of 3D heritage puzzles. The input to the workflow is an authentic artefact from a heritage collection, which is then digitised using technologies such as 3D scanning and 3D modelling. Thereafter, a puzzle generator produces the 3D puzzle pieces using a cell fracture algorithm and generates a set of puzzle pieces (female) and a single core piece (male) for fabrication. Finally, the pieces are fabricated using 3D printing technology and post-processed to facilitate the puzzle assembly. To demonstrate the workflow, we deploy the proposed method to create a 3D puzzle of an artefact, the Saltdean urn, for the Archaeological Gallery of the Brighton Museum and Art Gallery. The significance of this research is that it eases the task of creating puzzle-like activities and maintaining them within a busy museum gallery.

CCS Concepts

•**Computing methodologies** → *Shape modeling; Mesh geometry models*; •**Applied computing** → *Computer-aided design; Fine arts*;

1. Introduction

The technological advancements over the last years in 3D printing along with the attention that its applications have attracted from various communities, have resulted in making digital fabrication a popular topic of research, practice and discussion. Even though there is still a need to deal with several related obstacles, such as design knowledge, cost and available materials, before the widespread adoption of digital fabrication in people's everyday lives, the Cultural Heritage (CH) domain has proved to be a valuable field to try digital fabrication technologies. These technologies have already

been implemented in a variety of processes in the CH sector from conservation and exhibition planning to packaging and creative or educational activities [NL13, SCP* 14, NRRK14, SCP* 15].

This paper is concerned with the development of an application of digital fabrication which aims to contribute to the educational and communicational aspect of the CH experience. In particular, it examines how digital 3D models of artefacts can be re-purposed in creative ways in order to expand the benefits of the digitisation process. As such, the paper proposes the playful use of a 3D puzzle to enable users to experience the physical pieces or shards of

a pot in a similar way that archaeologists do when uncovering and synthesizing an artefact found at an excavation site. This requires digitally breaking a 3D shape into pieces and physically fabricating them in such a way that the puzzle can be easily re-assembled.

The technical contribution of this paper is a workflow for generating and fabricating the physical puzzle when the given input is an authentic museum artefact. The design of the 3D puzzle is driven by the main requirement which is to be easily assembled by a young person or child. The workflow is deployed with a late Iron Age burial urn from the area of Sussex (UK) - a significant object from the Brighton Museum and Art Gallery collection. The generated puzzle will be incorporated into the archaeological exhibition at the museum and is targeted to enhance young audiences' visiting experience while engaging them in an educational activity.

The paper is organised as follows. Section 2 discusses relevant work in the field including 3D printing technologies to communicate cultural heritage information and engage audiences. Section 3 introduces the particular artefact which drove the requirements for the development of the puzzle generating workflow and the audience of the application. Section 4 then presents the proposed workflow for the design and fabrication of the puzzle, including the 3D scanning of the artefact, its reconstruction and an algorithm for generating the puzzle. Section 5 discusses the evaluation of the application and the advantages of the adopted approach. Finally, section 6 presents discussions and conclusions.

2. Related work

2.1. Digital fabrication to communicate CH information

Digital fabrication technologies comprise a combination of programmable digital tools, processes, materials and equipment which allow the creation of physical objects of complexities not achievable by traditional manufacturing processes.

The interest from the CH community in these technologies is high as they offer the ability to manipulate the digital representation of an artefact in creative ways. In addition, these technologies enable a high-level of customisation when producing physical objects in a variety of resolutions, materials, colours and densities. Another important advantage of digital fabrication includes the possibility for multiple replication and/or production in a cost effective way, while "future-proofing" the information related to the artefact itself. Hence, these technologies are driving new trends for the mass-customisation of CH objects and experiences.

The term "smart" replicas has also become popular over the recent years. This refers to the possibility of combining the physical object with further layers of interpretative multimedia information [CNP15, MDC*16].

Moreover, digital fabrication applications to support the interpretation and communication of CH can be found in many heritage organisations around the world. These examples include applications, such as the full 3D print of the Sarcophagus of the Spouses from the Villa Giulia Etruscan Museum, which can support visitors in having a more holistic approach (by vision and touch) for the interpretation of an artefact [GBD*14].

Another example involves audiences in scanning objects and

mixing 3D models to produce hybrid artefacts by using digital fabrication. These activities can be oriented to people with knowledge of 3D tools, such as artists participating in 3D scanning and printing Hackathons [Mul12, NL13]. However, some institutions (e.g. British Museum and the Art Institute of Chicago) deploy 3D printing in order to involve groups in workshops for non-experts. Such groups include teachers, teenagers and families who engage with the museums' collections through 3D technology [Bri16, NR15, MKR*15].

Other examples employ 3D printed artefacts in educational programmes for children. The American Museum of Natural History asked students to capture and replicate dinosaur fossils from the museum's paleontology collections in order to synthesise a dinosaur and learn to think like paleontologists [AMN13]. Another application is a megalithic freestanding stone from Wales (UK) that was 3D printed in the form of a vertical puzzle that could be assembled by children using a central pillar [MKR*15].

Visually impaired audiences as well as the elderly constitute groups that can also benefit greatly from digital fabrication. Tooteko facilitates the navigation on an architectural 3D printed facade, allowing blind users to listen to audio descriptions [DBGV15]. 3D printed reliefs, with complementing interactive applications, support visually impaired users to feel paintings and natural history exhibits [RFMP16, SRSE17].

At the same time, digitally fabricated artefacts can work as engagement vehicles for elder audiences or trauma survivors while experiencing the "healing" properties of object handling and reminiscence [Ple16].

Alternative uses of replicas include the production of edible artefacts, such as the ones created at the MediaLab of The Metropolitan Museum of Art in New York, aiming to support the understanding of artefacts by providing a multisensorial experience to visitors [TZ15]. More "traditional" examples can be found in museums' shops, where replicas are sold as souvenirs or decorative/collection objects [You17].

Lastly, replicas have also served purposes related to the repatriation of original artefacts. In these cases, replicas are kept in the possession of the organisation while the original artefact returns to its possessor (the opposite can happen as well) [HEJ*13].

The breadth and spread of applications demonstrates i) the wide variety of experiential frameworks to provide people with the opportunity to "meet" and "feel" culture in alternative ways, and ii) the potential of digital fabrication technology to support the interpretation of a CH object and engage audiences. The development of digitally fabricated puzzles for audiences is a novel contribution to the wider efforts in this area.

2.2. Design challenges and relevant cases

The creation of a digitally fabricated puzzle can be achieved by different methods and tools. An important overall requirement is the generation of the puzzle pieces and the mechanism for their assembly. The graphics' community has previously conducted relevant research. For instance, the generation of interlocking parts from a 3D model has been a popular topic over the last years, as it

is not currently possible to print a single object that is larger than the working volume of a 3D printer. As such, various systems are proposed which take as an input a 3D model and produce various smaller interlocking pieces for 3D printing [SFLF15, LBRM12, ACP* 14, SCGT15]. Moreover, [XLF* 11, SFCO12, SZ15] present various algorithms for generating puzzles with interlocking pieces, known as burr puzzles, from a 3D model.

Most of the proposed solutions aim to create puzzles consisting only of the required individual pieces. However, in our case we aim to create a permanent exhibit of a pottery vase for a busy museum gallery. This means the puzzle should be easy to assemble by providing a clue of the overall shape, and the concave nature of the shape means that it can wrap around a static core element.

Similar examples of pottery puzzles in other museums (though without deploying a fully digital workflow) are shown in Figure 2. As shown in the images, these puzzles require a static element (the core) that provides a clue of the overall shape of the pot. Moreover, the core helps the user to assemble the puzzle with the use of magnets on its surface and on each puzzle piece.



Figure 2: a) Puzzle-pot from the Bristol Museum & Art Gallery (UK), photo courtesy of Andrew Maxted; b) puzzle-pot from Rezé Museum (France), photo courtesy of Theophane Nicolas

The contribution of this paper is the proposed workflow to generate a 3D puzzle of a pot, which is a popular type of archaeological artefact. This particular type of object is interesting as it is widely found in all historic societies and its reconstruction from shards is a problem often faced by archaeologists. The following section will present more details on the particular object and the design of the experience.

3. The 3D puzzle experiential framework

A funerary urn, shown in Figure 3, from the collection of the Brighton Museum and Art Gallery has been selected in order to design an experience that will engage young audiences in assembling a digitally fabricated 3D puzzle of the urn's replica. The urn comes from the cliff top at Saltdean, a coastal area near Brighton in Sussex, UK. The pot has curvilinear designs which are usual in Sussex in the two centuries BC, before the arrival of the Romans. The urn is mostly brown and it seems that burnishing had

been applied to its surface to give it a “leathery” appearance. The Saltdean funerary urn is a late Iron Age pot (probably 1st century BC) which was thrown on a wheel [Tom12]. It possibly reflects influences from Belgian tribes and people from Brittany who had moved into the area and introduced the use of the potter's wheel in south Britain [Har74, Cun78, AA82, Cun95].



Figure 3: Late Iron Age funerary urn from Saltdean, Sussex (UK)

The 3D puzzle will be a hands-on activity incorporated in the Archaeological Gallery of the Brighton Museum and Art Gallery. The puzzle will be placed along local findings of the Iron Age period and will be close to the original artefact.

The objective for the development of the puzzle is to support young audiences, and especially children, in having an interactive experience with a heritage artefact in the form of an educational activity or game. It will also allow wider audiences to experience the challenges linked to archaeological processes, such as reconstructing a shape from a given group of shards or pieces. By assembling the puzzle, audiences will engage with the exhibit, its physicality, function and history, while acquiring new skills and gaining a better understanding about the artefact itself.

3.1. Requirements for the production of the digitally fabricated 3D puzzle

The main design requirements with respect to the 3D puzzle were agreed between the researchers and the exhibition designers taking into account design guidelines about children's puzzles [Smi02]. These requirements included:

1. to have the urn height scaled-up to around 300 mm (the rest of the dimensions of the artefact were scaled-up proportionally);
2. to have a thickness of around 10 mm for each individual piece, as this was found suitable for easy handling by small hands;
3. to have approximately 10-12 pieces to assemble the puzzle. Thus, pieces should measure at least 50.8 mm across, as 6-8 year olds can handle pieces of this size;
4. to design a core piece which will be attached to a rotating wooden plate so that the user can easily spin the puzzle core to facilitate interaction (see Figure 4);
5. to enable attachment of the individual puzzle pieces to the core

via magnets. The magnets are inserted in blind holes in the puzzle pieces and in the solid core. The blind holes require to be in predetermined matching positions both in the pieces and core;

6. to cover each individual piece in a plaster-like finish and paint it to disguise the magnets, provide better texture feeling and a more realistic appearance.

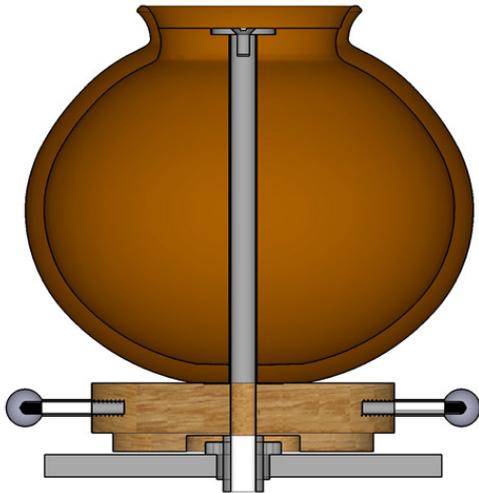


Figure 4: Design of puzzle core piece on its rotating base, design courtesy of Alex Hawkey

When discussing with the designer of the museum, it was acknowledged that such requirements could be addressed by using alternative mechanisms to digital fabrication technologies providing similar durability and quality. However, it was deemed that the digital workflow will enable to future-proof such exhibit for replacing parts in a cost-effective manner.

3.2. Audience

The target group for this puzzle activity are young people, in particular children between the age of 6 and 12 years old. This age frame is considered as appropriate in terms of integrating a specific type of interpretation as interpretative means can be different for younger or older children [Til77].

The selection of this particular group, whether it is families or school children visiting the museum, has been recognised as an important part of most CH organisations' audiences. Children appear to be amongst the people who can benefit the most from CH experiences with the deployment of replicas [CJ13, NR15, MKR* 15].

Furthermore, official numbers (in the "Overview of data in the Museums, Libraries and Archives Sector" [Mat04]) confirm that most people who visit a museum/CH institution in the UK belong to a family group or a school group. Hence, the Brighton Museum and Art Gallery has a high numbers of families and school children visiting its premises. Moreover a survey, realised in summer 2015 to record visitors' opinions on the potential to exhibit the archaeological collections of the museum, revealed that people would be interested in hands-on children's activities [Roy15].

The following section will describe a digital fabrication workflow to produce the 3D puzzle according to the specified requirements, along with a proposed algorithm to semi-automate the design of such 3D puzzles.

4. Workflow for generating and fabricating a 3D puzzle of an archaeological pottery artefact

The proposed workflow involves the following steps:

1. Acquiring and reconstructing the digital 3D model of the artefact.
2. Generating the individual puzzle pieces.
3. Generating matching blind-holes both in the core and puzzle pieces.
4. 3D printing all puzzle pieces and core.
5. Post-processing all puzzle pieces and core, which includes inserting the magnets.
6. Assembling the puzzle into the final exhibit.

The following sub-sections will describe each of these stages in detail.

4.1. Acquiring the digital 3D model of the artefact

The acquisition of an artefact can be achieved through different means, including 3D scanning and photogrammetry techniques. In this case, the urn was scanned using the AICON Breuckmann 3D SmartScan scanner. Given the shape of the urn with the narrowed neck above its rounded body, the 3D scanning process captured the external surface of the pot, but it was not possible to acquire the internal surface. The resulting 3D model is shown in Figure 1-a after some small holes were filled in.

In order to reconstruct the internal part of the urn which was not acquired by the scanner, it was considered that the best approach was to solidify the external wall at a suitable thickness using the 3D modelling tool Blender. Before doing this, the 3D model was scaled-up to have a 300 mm height according to the design requirements. Then, using the physics capabilities of Blender to simulate real-world phenomena, the 3D model of the urn (whose base is not completely straight) was placed on a plane in order to acquire a standing position (see Figure 5). Then, the top of the urn's rim was removed in order to isolate the external shell of the urn.

Subsequently, the external shell was solidified with a 10 mm thickness in Blender. This thickness is proportionally close to the scaled-up measurements of the artefact. Afterwards, two 3D models were produced:

- The urn without rim. The rim was later joined again with the urn and modeled to have a smooth feeling in order to produce the reconstructed 3D model of the pot (see Figure 6-a).
- The internal shell of the pot which constitutes the core of the puzzle. Thus, the faces of the internal shell were inverted in Meshlab and a plane was added to the top of the shape to create a water-tight core (see Figure 6-b).

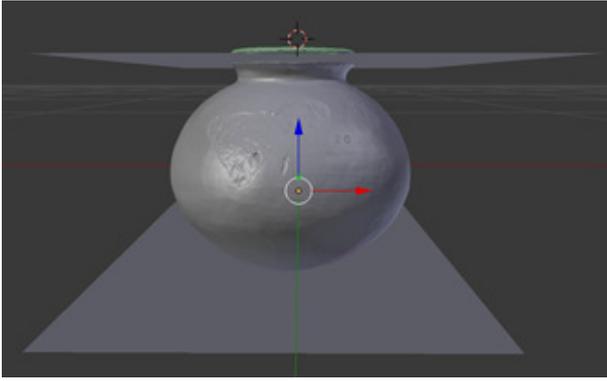


Figure 5: *Perspective view of the urn with separated rim in Blender*

4.2. Generating the individual puzzle pieces

In order to generate the puzzle pieces, a semi-automated approach was deployed using OpenSCAD software. OpenSCAD is a free Computer Aided Design (CAD) software which uses the Computational Geometry Algorithms Library (CGAL) as its constructive solid geometry (CSG) engine. Its script syntax is based upon functional programming philosophy which allows to generate geometry using a functional approach.

The proposed approach takes as input the watertight 3D models of the reconstructed urn (Figure 6-a) and core (Figure 6-b), both generated in the previous steps. The generator then produces:

- 14 individual puzzle pieces. Four of these pieces are retained to be used for the base of the puzzle. The user will have this base as a reference when assembling the rest of the puzzle pieces. The remaining ten pieces are generated with up to 6 holes each for fitting the magnets.
- A core with a through-hole along its height and up to 60 matching blind-holes distributed across the surface to fit the magnets.

To generate the puzzle pieces, firstly it is required to input a randomly fractured geometry of a spherical polyhedron. To achieve this, the cell fracture algorithm of a modeling tool (e.g. Blender) is applied on the polyhedron. The sphere is fractured into 14 pieces in this case. However, it is possible to generate more or less pieces, if smaller or larger puzzle pieces are desired.

As shown in Figure 7, a sphere is used as it provides good coverage of the geometry of the urn. Yet it is possible to use other alternative polyhedra (e.g. hexahedron) for other geometries. The 3D model is then fitted at the centre of the fractured sphere (see Figure 7).

Boolean operations are then used for generating the puzzle pieces and the internal core with matching blind holes. These sets of operations, including union, intersection and difference, are the basis of how geometries are constructed in CAD systems.

To generate each puzzle piece, the intersection operation is used. As shown in Figure 8-a, each section of the fractured sphere is intersected with the 3D model of the reconstructed urn. The intersection

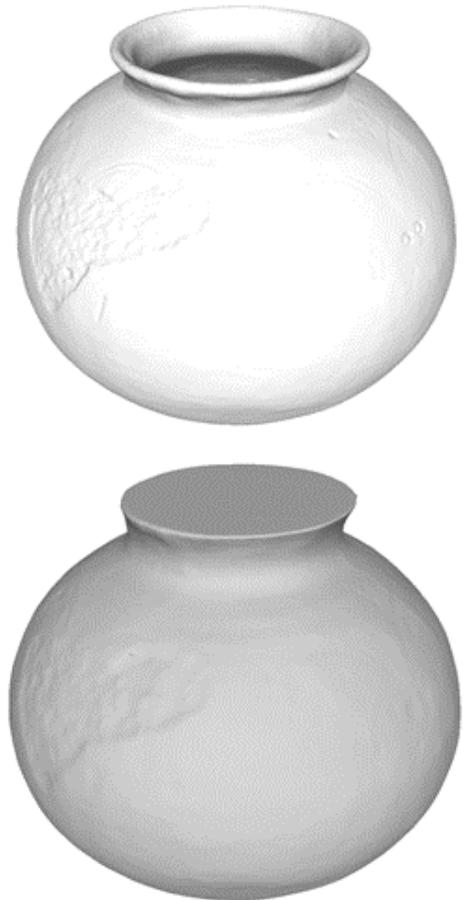


Figure 6: *a) 3D model of the reconstructed urn; b) the internal core of the puzzle*

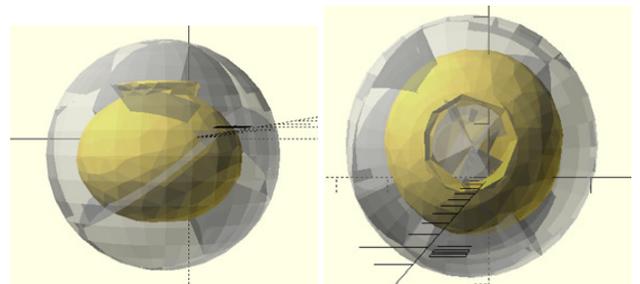


Figure 7: *3D model of the reconstructed urn positioned at the centre of the fractured sphere*

region of these two objects is defined as the set of all points that are part of both objects. As a result, a puzzle piece is produced as shown in Figure 8-b.

The algorithm iterates over all sections of the fractured sphere to automatically produce all puzzle pieces. This process is repeated to generate puzzle pieces at two different levels of detail so that they can be used in subsequent operations.

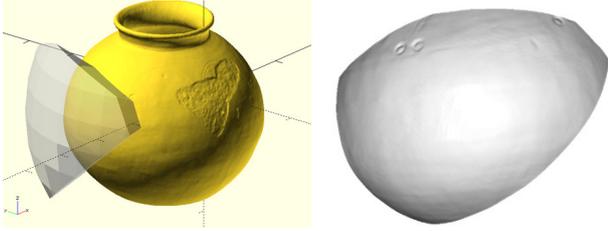


Figure 8: a) Intersection of 3D model of reconstructed urn and section of the fractured sphere; b) resulting puzzle piece

4.3. Generating matching blind-holes both in the core and puzzle pieces

Once all puzzle pieces have been produced, matching blind-holes are generated both for the individual puzzle pieces and the central core to fit the magnets in. The blind-holes have consistent width and depth which should be enough to hide the magnets in.

To generate the blind-holes across the surface, a set of points in 3D space is given as an input. This set of points should offer full coverage across the surface. The set can be randomly generated as random points on a sphere. However, given the requirement to have a specific number of holes for each piece, the positions were manually determined to ensure an even distribution. Each point is then used to generate a cylinder whose origin is the centre of the 3D model, as illustrated in Figure 9.

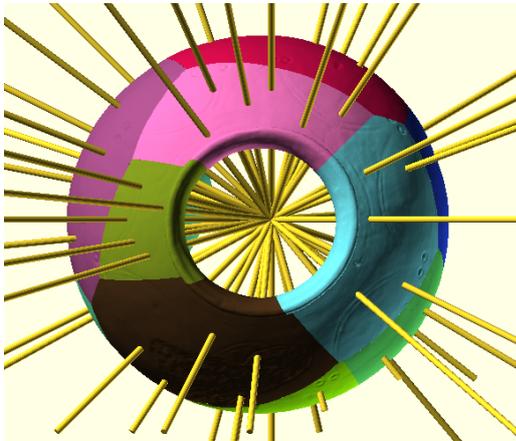


Figure 9: Cylinders generated using as input a set of points in 3D space

The algorithm to create the blind-holes is based on the intersection and difference operations. Hence, the algorithm can be described in Algorithm 1.

The algorithm produces an intersection between the cylinder and a simplified version of the puzzle piece for speed purposes. It then translates the resulting geometry of the interaction towards the origin by taking into account a thickness value. This code generates a geometry, which will later become the hole, for each cylinder as shown in Figure 10-a.

Data: 3D model of puzzle piece and set of 3D points

Result: 3D model of puzzle piece with blind holes

points: set of 3D points;

3dmodel: 3D model of puzzle piece simplified;

thickness: thickness of the blind hole;

for $i \leftarrow 0$ **to** $\text{length}(\text{points})$ **do**

point = $\text{points}[i]$;

unitvector = $\text{point}/\text{norm}(\text{point})$;

$\text{translate}(-\text{unitvector} * \text{thickness})$

$\text{intersection}(\text{3dmodel}, \text{cylinder}(\text{point}.x, \text{point}.y, \text{point}.z))$;

end

Algorithm 1: Algorithm pseudo-code to generate geometries for blind-holes in puzzle pieces

These generated geometries are then used to generate the blind-holes. This is achieved by using the difference operation between the 3D puzzle piece and the generated geometry (see Figure 10-a and b). The same process is repeated for all the puzzle pieces. This step produces all puzzle pieces with the required holes (see Figure 1-c).

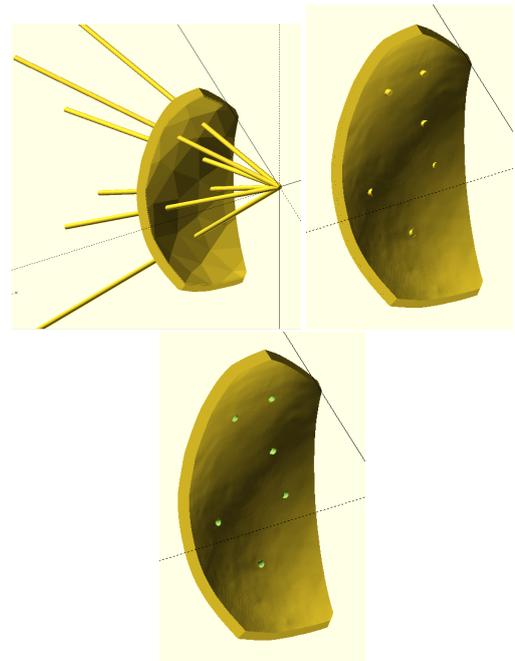


Figure 10: a) Puzzle piece with cylinder for blind-holes; b) puzzle piece with geometry generated for the creation of each blind-hole; c) puzzle piece with blind-holes

Furthermore, a similar process is repeated for generating the blind-holes in the core piece using the same 3D points. However, this time the direction in which the intersected geometry is translated is reversed. The resulting geometry is shown in Figure 11. The core also requires a through central hole for fixing it to the rotating base.

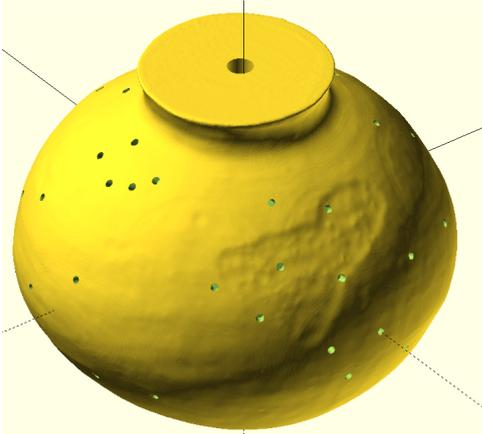


Figure 11: Core with blind-holes across the surface

4.4. 3D printing puzzle pieces and core

Before printing all puzzle pieces, a sample set of pieces were 3D printed to validate the dimensions of the holes as well as to check whether the overall dimensions and weight were suitable for the purposes of the activity (see Figure 12-a). Some minor adjustments were made to the dimensions of the holes to take into account the thickness of the printed layers for the print. This thickness usually depends on the nozzle size and the machine and will vary for different printing technologies.

Finally, all the puzzle pieces were 3D printed, as shown in Figure 1-c. Although the core could be printed all at once, it was split into eight sections to achieve better printing quality (and less supporting material) by allowing each section to be positioned flat on the printer's bed (see Figure 12-b).

All pieces were printed in PLA (Polylactic Acid) filament on a FDM (Fused Deposition Modeling) 3D printer at a 0.2mm layer thickness with an infill value of 12%. The core piece was printed at a 0.4 mm layer thickness.

4.5. Post-processing all puzzle pieces and core

Post-processing of the puzzle pieces and the core includes removing the supporting material around the pieces and sanding any rough surfaces. Then, the magnets are inserted in holes at the back of each puzzle piece and on the core. The holes are covered afterwards with plaster and sanded accordingly.

When the plaster has dried, a coating using a mixture of PVA (Polyvinyl acetate) glue, marble powder and water is applied on the puzzle pieces and core in order to provide a ceramic-like texture. Figure 13 demonstrates the samples that were 3D printed using PLA filaments in different colours. The sample on the top right of the image has been chosen for the puzzle pot. The sample has been coated with the described mixture and painted using acrylic colours. The pieces are currently being post-processed to achieve the same visual quality as the samples.



Figure 12: a) 3D printed set of samples with cylinders generated using as input a set of points in 3D space; and b) printed core piece

5. Evaluation

The puzzle, its design and performance have been mainly tested with the design team and the curators of the museum. The functional testing has been an iterative process throughout the digital fabrication workflow to see whether the requirements of the activity/exhibit have been met. The feedback from this process has informed design decisions at subsequent steps of the workflow.

The evaluation of the puzzle pot activity and its performance in terms of enhancing the visiting experience for families of the Archaeological Gallery of the Brighton Museum and Art Gallery will take place once the Gallery is open to the public. A detailed method for the evaluation has already been set up and tested with another museum [SRSE17].

A final consideration is given to how this solution compares to other fabrication methods of archaeological puzzles. For instance, a similar puzzle to the one produced could be made using a more traditional approach: by modeling a pot from a hard wearing clay, firing and glazing it. This pot could then be smashed, reassembled

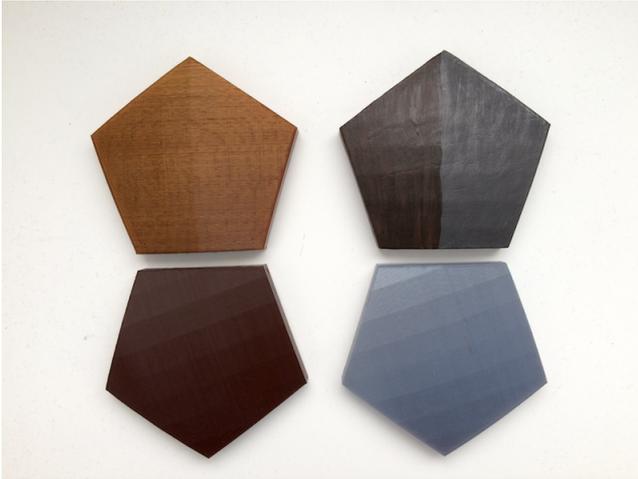


Figure 13: *Selecting the appropriate colour and texture for the puzzle pieces*

and a core could then be made. This process is not very expensive, as it would probably cost one third of the cost of our proposed approach, and also requires only access to clay and a kiln. However, the puzzle pieces would not have very good quality. For instance, the pieces would not necessarily break with the dimensions required and in equal sizes, the magnets would be difficult to fit neatly. Most importantly, if a single piece disappeared from the gallery, the process to replace the piece would be costly and complex.

Alternatively, it is possible to make a pot using clay and produce a mould or negative using plaster of Paris or silicone. Tin would then be used to make the shard shapes in the mould. The puzzle pieces and core would then be casted in jesmonite. Holes for the magnets would then be drilled in the casted material. Although this process is slightly more expensive than the previous one, it would be possible to replace a piece if this was lost. However, the mould would require to be carefully guarded so it does not get lost, and it would suffer of inevitable wear out. The latter issue would affect the reproduction of subsequent copies of puzzle pieces.

The proposed approach has the following advantages in relation to the previous approaches: i) it uses an authentic artefact of the collection, ii) it is far simpler and more cost-effective making multiple copies or replacements once the digital design and testing is done, iii) it allows the generation of puzzles of other shapes and sizes in a more cost-effective way, and iv) the digital model is a valuable outcome by itself, for instance it can be used in interactive puzzle-making applications on the web and can be shared with other museums in case they wanted to replicate the physical experience.

6. Discussion and conclusions

This paper presented a novel digital workflow for the generation of 3D puzzles for museum galleries. The workflow was deployed with a particular artefact, the Saltdean urn. The 3D puzzle activity will be exhibited at the Brighton Museum and Art Gallery.

The proposed workflow's input is an artefact which is digitised and converted into a digital format. A series of steps are then employed in order to produce a watertight model of the artefact and a core for the puzzle pieces to "sit on". An algorithm is then proposed to generate the puzzle fragments or shards and the blind-holes for the magnets on the pieces and core. These steps make use of a combination of cell fracture algorithms and the Boolean operations provided by CAD systems.

One of the challenges of the workflow is producing the watertight 3D mesh suitable for the generation of the puzzle. This is because this 3D mesh is not a straight-forward outcome from the digitisation processes. Due to these challenges, the urn's shape had to be reconstructed to a certain extent to fill-in gaps which the digitisation process did not capture, such as parts of the rim and the inner-surface. The shape was also slightly simplified to make it easier to handle in the modeling stage. The fabrication process also requires considering tolerances due to the layer size of the 3D printing technology.

The significance of the proposed workflow is that it can provide a CH organisation with a cost-effective "future-proof" solution. Hence, the process can be easily repeated either to replace lost pieces of the puzzle or replicate the whole exhibit with minor changes. Moreover, the presented process is relatively low cost in comparison to other traditional design and production methods and can be deployed to enhance the interpretation of artefacts in heritage environments.

Future work will examine the effect that such an object and activity have in engaging young audiences as well as investigating the audience's opinion about the physical characteristics of the puzzle.

7. Acknowledgments

We thank the Brighton Museum and Art Gallery, and in particular Alex Hawkey and Andrew Maxted, for their input and support during the development of the research.

References

- [AA82] ADKINS L., ADKINS R.: *The handbook of British archaeology, Originally published as 'A thesaurus of British archaeology'*. David & Charles, Newton Abbot, 1982. 3
- [ACP*14] ALEMANNI G., CIGNONI P., PIETRONI N., PONCHIO F., SCOPIGNO R.: Interlocking Pieces for Printing Tangible Cultural Heritage Replicas. In *Eurographics Workshop on Graphics and Cultural Heritage* (2014), Klein R., Santos P., (Eds.), The Eurographics Association. doi:10.2312/gch.20141312. 3
- [AMN13] AMNH: Students Use 3D Printing to Reconstruct Dinosaurs, 2013. URL: <http://www.amnh.org/explore/news-blogs/education-posts/students-use-3d-printing-to-reconstruct-dinosaurs>. 2
- [Bri16] BRITISH MUSEUM: Digital workshop - Teens 3D scanning skills workshop, 2016. URL: http://www.britishmuseum.org/whats_on/events_calendar/event_detail.aspx?eventId=2808. 2
- [CJ13] CABRAL M., JUSTICE S.: Material Learning: Digital 3D With Young Children. *Fablearn.Stanford.Edu* (2013), 3–6. URL: <http://fablearn.stanford.edu/2013/wp-content/uploads/MATERIAL-LEARNING-DIGITAL-3D-WITH-YOUNG-CHILDREN.pdf>. 4

- [CNP15] CAPURRO C., NOLLET D., PLETINCKX D.: Tangible Interfaces for Digital Museum Applications. In *2015 Digital Heritage* (2015). 2
- [Cun78] CUNLIFFE B.: *Iron age communities in Britain: An account of England, Scotland and Wales from the seventh century BC until the Roman conquest*. Routledge & Kegan Paul, London; Boston;, 1978. doi:10.4324/9780203326053.3
- [Cun95] CUNLIFFE B.: *Book of Iron Age Britain*. B.T. Batsford, London;, 1995. 3
- [DBGV15] D'AGNANO F., BALLETTI C., GUERRA F., VERNIER P.: Tooteko: A case study of augmented reality for an accessible cultural heritage. Digitization, 3D printing and sensors for an audio-tactile experience. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives* 40, 5W4 (2015), 207–213. doi:10.5194/isprsarchives-XL-5-W4-207-2015.2
- [GBD*14] GUIDAZZOLI A., BAGLIVO A., DE LUCA D., IMBODEN S., LIGUORI M. C., A. R.: Crossmedia integration of 3D contents for cultural communication. In *3DTV-Conference: The True Vision - Capture, Transmission and Display of 3D Video (3DTV-CON)* (Budapest, 2014), no. 2-4 July 2014, pp. 1–4. URL: [#](http://ieeexplore.ieee.org/xpls/icp.jsp?arnumber=6874732)citedby-section.2
- [Har74] HARDING D.: *The Iron Age in lowland Britain*. Routledge & Kegan Paul, London;, 1974. 3
- [HEJ*13] HOLLINGER R. E., EDWELL JOHN J., JACOBS H., MORAN-COLLINS L., THOME C., ZASTROW J., METALLO A., WAIBEL G., ROSSI V.: Tlingit-Smithsonian Collaborations with 3D Digitization of Cultural Objects. *Museum Anthropology Review* 7, 1-2 (2013), 201–253. URL: <https://scholarworks.iu.edu/journals/index.php/mar/article/view/2173>. 2
- [LBRM12] LUO L., BARAN I., RUSINKIEWICZ S., MATUSIK W.: Chopper: Partitioning Models into 3d-Printable Parts. *ACM Transactions on Graphics (Proc. SIGGRAPH Asia)* 31, 6 (Dec. 2012). doi:10.1145/2366145.2366148. 3
- [Mat04] MATTY S.: *Overview of Data in the Museums, Libraries and Archives Sector*. Tech. rep., 2004. URL: [www.mla.gov.uk/documents/ev\(_\)stats\(_\)overview.doc](http://www.mla.gov.uk/documents/ev(_)stats(_)overview.doc). 4
- [MDC*16] MARSHALL M. T., DULAKE N., CIOLFI L., DURANTI D., KOCKELKORN H., PETRELLI D.: Using Tangible Smart Replicas as Controls for an Interactive Museum Exhibition. *Tei'2016* (2016), 159–167. doi:10.1145/2839462.2839493. 2
- [MKR*15] MILES H. C., KARL R., ROBERTS J. C., WILSON A. T., LABROSSE F., TIDDEMAN B., GRIFFITHS S., EDWARDS B., RITZOS P. D., MEARMAN J. W., MÖLLER K.: Alternative Representations of 3D-Reconstructed Heritage Data. *Journal on Computing and Cultural Heritage* 9, 1 (2015), 1–18. URL: <http://dl.acm.org/citation.cfm?id=2846105.2795233>, doi:10.1145/2795233.2,4
- [Mul12] MULLANEY J.: The High-Tech Met, 2012. URL: <http://www.metmuseum.org/blogs/now-at-the-met/features/2012/high-tech-met>. 2
- [NL13] NEELY L., LANGER M.: Please Feel the Museum : The Emergence of 3D Printing and Scanning. *Museums and the Web 2013* (2013). 1,2
- [NR15] NEELY L., ROZNER E.: Museum3D: Experiments in engaging audiences using 3D. *Museums and the Web 2015* (2015). 2,4
- [NRRK14] NEUMULLER M., REICHLINGER A., RIST F., KERN C.: 3d Printing for Cultural Heritage: Preservation, Accessibility, Research and Education. *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)* 8355 (2014), 119–134. URL: <http://www.scopus.com/inward/record.url?eid=2-s2.0-84921472127&partnerID=40&md5=11a46dfa39a37f83aa151807a9c8eac0>. 1
- [Ple16] PLEASE TOUCH: The Please Touch Project presents Stories in Process | Events | Sheffield Institute of Arts | Sheffield Hallam University, 2016. URL: <https://www4.shu.ac.uk/sia/events/event-listing.html?event=218>. 2
- [RFMP16] REICHLINGER A., FUHRMANN A., MAIERHOFER S., PURGATHOFER W.: Gesture-Based Interactive Audio Guide on Tactile Reliefs. In *Proceedings of the 18th International ACM SIGACCESS Conference on Computers and Accessibility - ASSETS '16* (2016), pp. 91–100. URL: <http://dl.acm.org/citation.cfm?doid=2982142.2982176>, doi:10.1145/2982142.2982176. 2
- [Roy15] ROYAL PAVILION AND MUSEUMS: *Archaeology Survey 2015*. Tech. rep., 2015. 4
- [SCGT15] SKOURAS M., COROS S., GRINSPUN E., THOMASZEWSKI B.: Interactive Surface Design with Interlocking Elements. *ACM Trans. Graph.* 34, 6 (Oct. 2015), 224:1–224:7. URL: <http://doi.acm.org/10.1145/2816795.2818128>, doi:10.1145/2816795.2818128. 3
- [SCP*14] SCOPIGNO R., CIGNONI P., PIETRONI N., CALLIERI M., DELLEPIANE M.: Digital Fabrication Technologies for Cultural Heritage (STAR). In *12th Eurographics Workshops on Graphics and Cultural Heritage (EG GCH 2014)* (2014), Santos R. K., Pedro, (Eds.), Eurographics Association, pp. 75–85. 1
- [SCP*15] SCOPIGNO R., CIGNONI P., PIETRONI N., CALLIERI M., DELLEPIANE M.: Digital Fabrication Technologies for Cultural Heritage: A Survey. *Computer Graphics Forum* xx, z (2015), 1–17. 1
- [SFCO12] SONG P., FU C.-W., COHEN-OR D.: Recursive interlocking puzzles. *ACM Trans. Graph.* 31, 6 (Nov. 2012), 128:1–128:10. URL: <http://doi.acm.org/10.1145/2366145.2366147>, doi:10.1145/2366145.2366147. 3
- [SFLF15] SONG P., FU Z., LIU L., FU C.-W.: Printing 3d objects with interlocking parts. *Comput. Aided Geom. Des.* 35, C (May 2015), 137–148. URL: <http://dx.doi.org/10.1016/j.cagd.2015.03.020>, doi:10.1016/j.cagd.2015.03.020. 3
- [Smi02] SMITH T. P.: *AGE DETERMINATION GUIDELINES: Relating Children's Ages To Toy Characteristics and Play Behavior*. Tech. Rep. September, 2002. 3
- [SRSE17] SAMAROUDI M., RODRIGUEZ ECHAVARRIA K., SONG R., EVANS R.: The fabricated diorama : Tactile relief and context-aware technology for visually impaired audiences. In *Eurographics Workshop on Graphics and Cultural Heritage* (Graz, 2017), Schreck T., Weyrich T., Sablatnig R., Stular B., (Eds.), The Eurographics Association. doi:10.2312/gch.20171315.2,7
- [SZ15] SUN T., ZHENG C.: Computational Design of Twisty Joints and Puzzles. *ACM Trans. Graph.* 34, 4 (July 2015), 101:1–101:11. URL: <http://doi.acm.org/10.1145/2766961>, doi:10.1145/2766961. 3
- [Til77] TILDEN F.: *Interpreting our heritage*. University of North Carolina Press, Chapel Hill, 1977. doi:973.07TIL.4
- [Tom12] TOMS H. S.: Notes on a Late Celtic Urn found near Brighton. *The Antiquary* 8, Jun (1912), 223–226. 3
- [TZ15] TANG J., ZHAO Y.: Edible Met: Eating Art to Understand, 2015. URL: <http://www.metmuseum.org/blogs/digital-underground/2015/edible-met>. 2
- [XLF*11] XIN S., LAI C.-F., FU C.-W., WONG T.-T., HE Y., COHEN-OR D.: Making burr puzzles from 3d models. *ACM Trans. Graph.* 30, 4 (July 2011), 97:1–97:8. URL: <http://doi.acm.org/10.1145/2010324.1964992>, doi:10.1145/2010324.1964992. 3
- [You17] YOUNG J.: British Museum Now Offers 3D Printed Replicas of Parts of Its Collection, 2017. URL: <https://3dprint.com/182710/british-museum-3d-printing/>. 2