MS[Could it be something like: Workflow and fabrication of 3D puzzles to support interpretation of archeaological artefacts]

KR[let's change title to have a different name from the previous publication]Digital workflow for creating 3D puzzles to engage audiences in the interpretation of archaeological artefacts

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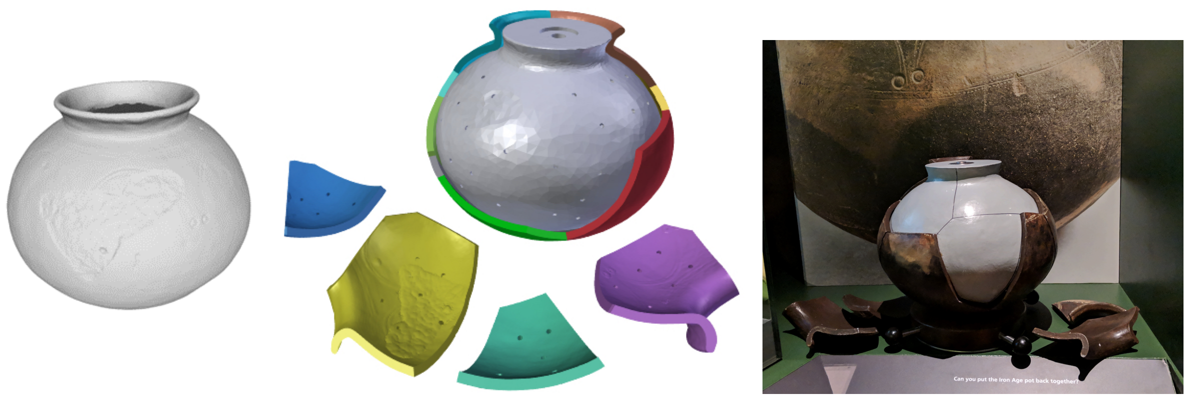

(a) 3D scanned urn model (b) Generated puzzle pieces and core (c) Fabricated puzzle in museum exhibition

Fig. 1. Workflow for the development of physical puzzles of pottery archaeological artefacts

3D physical puzzles are typically used to engage audiences in the interpretation of archaeological artefacts in a museum ~~exhibition~~gallery. The reason for this is that a puzzle can be seen as ~~a game~~an enjoyable educational activity in the form of a game but also as a complex activity that archaeologists undertake ~~to re-assemble~~when re-assembling fragments of broken pottery. The contribution of this paper is a novel ~~digital~~ worfklow for the design and fabrication of ~~3D~~physical

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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.KR[The following is to specific and needs to be rephrased to be more generic while keeping the saltdean pot at the centre of the deployment of the full workflow] To demonstrate the workflow, we ~~deploy~~deployed the proposed method to create a 3D puzzle of ~~an artefact,~~ the Saltdean urn, ~~for~~which is exhibited at the Archaeology Gallery of the Brighton Museum and Art Gallery.MS[Karina I added the following to do it more generic as well] The workflow is also used with further artefacts in order to demonstrate its applicability to other shapes and types of artefacts.The significance of this research is that it eases the task of creating puzzle-like activities and maintaining them in the long term within a busy museum gallery.

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

Additional Key Words and Phrases: cultural heritage, 3D printing, gallery design, hands-on activities, educational puzzles

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1 INTRODUCTION

The technological developments 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 [20, 22, 28, 29].

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~~has been incorporated into the Archaeology ~~exhibition at the museum and is targeted~~Gallery in order to enhance young audiences' visiting experience while engaging them in an educational activity.

In additionTW[describe that we explore different fracture patterns]

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 presents further examples where the algorithms have been applied in order to showcase the applicability of the workflow to other shapes and types of artefacts. Section 6 discusses the evaluation of the application and the advantages of the adopted approach. Finally, section 7 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 [6, 15].

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 [10].

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 [18, 20]. 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 [4, 17, 21].

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 [3]. 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 [17].

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 [9]. 3D printed reliefs, with complementing interactive applications, support visually impaired users to feel paintings and natural history exhibits [24, 26].

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 [23].

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 [36]. More "traditional" examples can be found in museums' shops, where replicas are sold as souvenirs or decorative/collection objects [40].

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) [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.

(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 Nicola

Fig. 2. Examples of pottery puzzles in museums

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 [2, 14, 31, 34]. Moreover, [33, 35, 39] present various algorithms for generating puzzles with interlocking pieces, known as burr puzzles, from a 3D model.

Another relevant area of research is the fracturing simulation ~~of fractures for~~of 3D models. These fracturing effects are often used to display the breaking or destruction of objects or places in computer games, virtual reality and the film industry. In this area, predefined fracture patterns are often computed, while more novel solutions focus on creating fast approximations which are computational efficient and offer flexible control of fragment generation [11, 19, 27, 41]. Of relevance to the heritage field is the geometric analysis of a dataset of fracture patterns observed in wall paintings excavated at Akrotiri, Greece [30]. This analysis suggests pottery fragments in a hierarchical fracture pattern, where fragments break into two pieces recursively along cracks nearly orthogonal to previous ones.

Most of the proposed solutions in literature aim to create puzzles consisting only of the required individual pieces.[MS] [As this really isn't an opposition to the previous sentence, I think that we should erase this "however"] ~~However,~~In our case, we aim to create a permanent hands-on exhibit ~~of a pottery vase~~ for a busy museum gallery. As pottery is a common archaeological finding at an excavation site, we focus on this type of artefact, and the shape of its fragments when broken into shards or pieces. This type of artefact is also interesting as its reconstruction from shards is a problem often faced by archaeologists.. ~~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~~might provide clues about the overall shape of the pot. Moreover, the core helps ~~the user to assemble the puzzle~~to secure the pieces in place with the use of magnets or other attachment mechanisms which are placed both on ~~its~~the core's surface and on each puzzle piece.

~~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 motivation to develop the proposed workflow stemmed from the need to design an ~~experience~~experiential framework that ~~will~~would engage young audiences with the archaeological collection of the Brighton Museum and Art Gallery. Thus, the requirement was to design a 3D puzzle of a funerary urn, shown in Figure 3. 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 [38]. 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 [1, 7, 8, 12].

Fig. 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 puzzle was designed to be placed as a hands-on activity along with local findings of the Iron Age period and close to the original artefact in the new Archaeology Gallery. The objective ~~for~~of the ~~development of the puzzle~~hands-on activity 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~~The puzzle ~~will~~also allows 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 [32]. 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~~would 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~~an appearance that would be as close as possible to the original one.

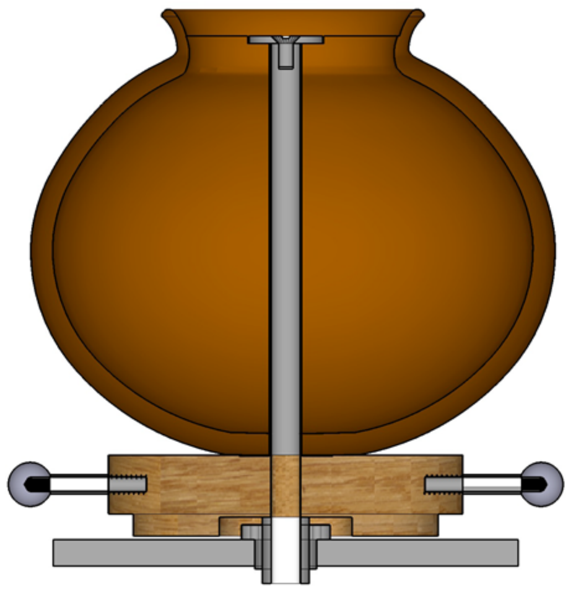


Fig. 4. Design of puzzle core piece on its rotating base, design courtesy of Alex Hawkey

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~~would 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 [37].

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 [5, 17, 21].

Furthermore, official numbers (in the "Overview of data in the Museums, Libraries and Archives Sector" [16]) 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 [25].

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~~Digitisation and ~~reconstructing~~reconstruction of the digital 3D model of the artefact and its central core piece.
(2) Generation of fracture pattern.
(3) Generation of the individual puzzle pieces.
(4) Generation of ~~matching blind-holes~~attachment mechanisms, such as matching blind holes, both in the core and puzzle pieces.
(5) 3D printing all puzzle pieces and core.
(6) Post-processing of all puzzle pieces and core~~, which includes inserting the magnets~~, including adding attachments and painting.
(7) Assembling the puzzle into the final exhibit.

The approach for ~~generating~~producing solid surfaces for fabrication, which underlies the proposed ~~workshop~~workflow, combines algorithms generating fracture patterns with constructive solid geometry (CSG) operations. CSG is a technique commonly used in solid modeling CAD systems. It allows to create a complex surface by using Boolean operators to combine simpler objects.

The implementation of the workflow uses a mixture of tools and systems including modelling tools, C++ and OpenSCAD. OpenSCAD is a CSG engine based on the Computational Geometry Algorithms Library. 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 following subs-sections will describe each of the workflow stages in detail using the Saltdean pot as an example artefact.

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

4.1 ~~Acquiring the digital 3D model~~Digitisation and reconstruction of the heritage 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~~with a 10 mm 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 ??). Then, the top of the urns rim was removed in order to isolate the external shell of the urn.~~The resulting 3D model which ~~will be~~has been used as input for the puzzle is shown in Figure 5a.

~~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 5a).~~

~~The internal shell of the pot which constitutes the core of the puzzle. Thus, the faces of the internal shell were inverted it Meshlab and a plane was added to the top of the shape to create a watertight core (see Figure 5b).~~Afterwards, the central core piece ~~is~~was produced. This can be generated for any type of pottery puzzle by using a boolean operation. The resulting watertight model is shown in Figure 5b. The core ~~requires~~required also of a through-hole along its height in order to fit ~~it to~~onto the revolving base, as shown in the design in Figure 4.

(a) 3D model of the reconstructed urn

(b) 3D model of internal core of the puzzle

Fig. 5. 3D models used for puzzle generation

4.2 Generation of fracture patterns

say:

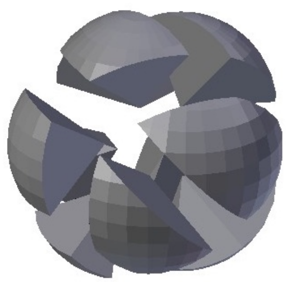
- we model fracture lines by projecting the pot's geometry onto a sphere; while this restricts us to mostly-spherical objects, it appears a reasonable approximation in our context.
- then describe different ways to create fractures
- visualise them by fracturing a perfect sphere, so we can show Blender fractures in the same way as our own:
  - Figure 1: Blender, vs. hierarchical, but show the latter with straight lines (almost(?) zero amplitude)
  - Figure 2: compare different fractal parameters

  leave comparison of differently fractured models for the results section.

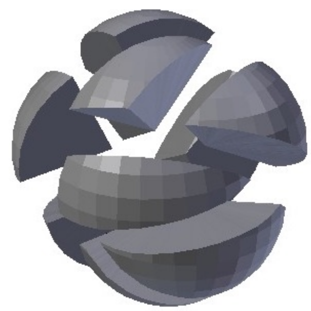
[KR][we can delete the following once the new section is in place.]To generate a puzzle pieces, firstly it is required to input a randomly fractured geometry of a spherical polyhedron. To achieve this, it is possible to use a cell fracture algorithm of a modeling tool (e.g. Blender). The sphere is fractured into 14 pieces in this case. However, it is possible to generate more or less pieces, if smaller or larger puzzle pieces are desired.

4.3 Generating the individual puzzle pieces

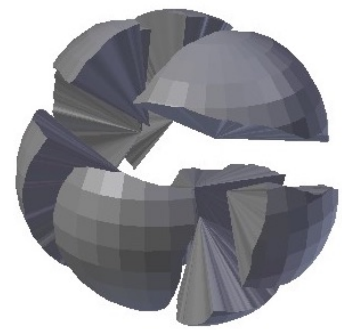
~~In order to generate the puzzle pieces, a semi-automated approach was deployed using OpenSCAD software. OpenSCAD is a free Computer Aided Design (CAD) software which uses the Computational Geometry Algorithms~~



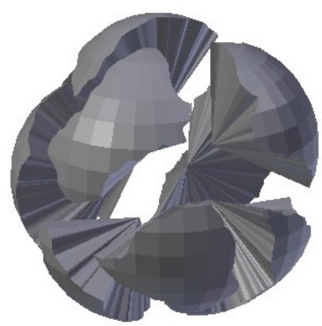
(a) Voronoi fracture pattern



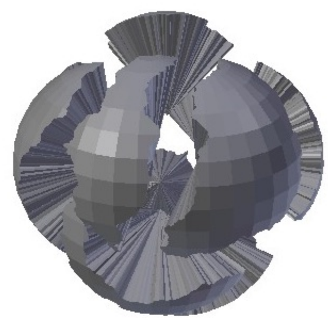
(b) Hierarchical fracture pattern, m: 6, nitter: 6, jitter: 0.3, amplitude: 0.01, decay: 0.5, smoothing: 0.0



(c) Hierarchical fracture pattern, m: 6, nitter: 6, jitter: 0.3, amplitude: 0.1, decay: 0.5, smoothing: 1.0



(d) Hierarchical fracture pattern, m: 6, nitter: 6, jitter: 0.3, amplitude: 0.2, decay: 0.2, smoothing: 1.0



(e) Hierarchical fracture pattern, m: 6, nitter: 6, jitter: 0.1, amplitude: 0.3, decay: 0.5, smoothing: 0.3

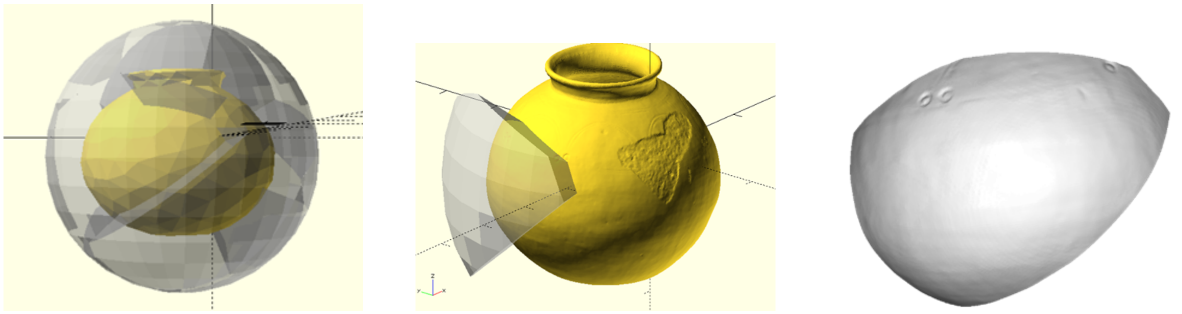
Fig. 6. Fracture patterns

~~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 ?? a) and core (Figure ?? b), both generated in the previous steps. The generator then produces:~~Once the fracture pattern has been generated, ~~this~~it is used to ~~generate~~produce the puzzle pieces.

~~Boolean operations are 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. For this, the 3D model is firstly translated to the centre of the fractured sphere (see Figure 7a). Thereafter, as shown in Figure 7b, each[KR][do I use the word "section" before, not sure this is correct][MS][Karina the word section hasn't been used, the word fracture is used above] ~~section of the fractured sphere~~fracture of the sphere is intersected with the 3D model of the reconstructed



(a) 3D model contained within all fragments of sphere

(b) 3D model of reconstructed urn with fragment of the fractured sphere

(c) Resulting 3D model of puzzle piece

Fig. 7. [KR][Need a better caption][MS][Could it be: Puzzle fragment generation through fracture pattern?]Process of generating each puzzle piece using fracture pattern

urn. The intersection 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 7c.

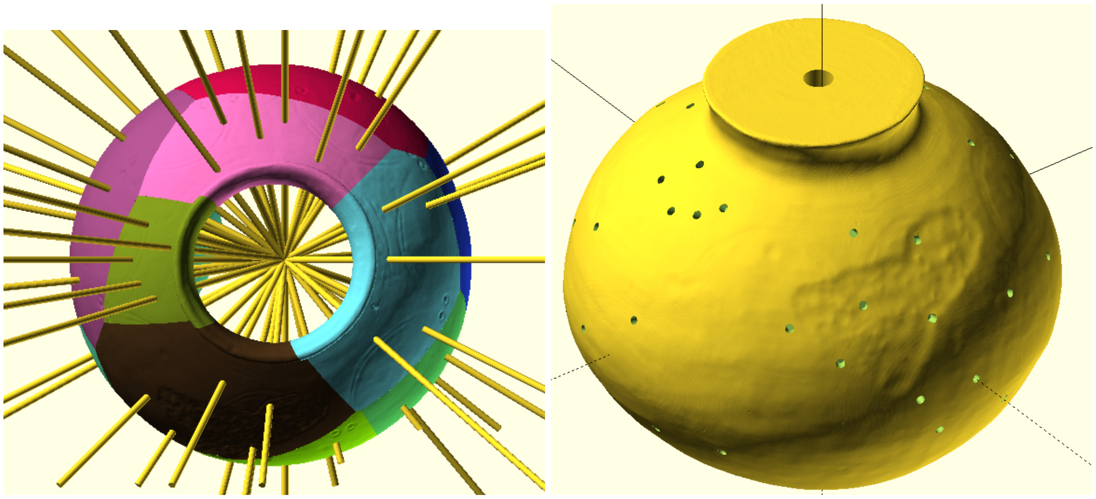
The algorithm iterates over all sections of the fractured sphere to automatically produce all puzzle pieces. This process is repeated to generate puzzle pieces at two different levels of detail so that they can be used in subsequent operations.

For the Saltdean urn, we generated ~~14~~16 individual puzzle pieces.[MS][In figure 11a we show 16 pieces, so I changed it to reflect that. The number of pieces for the base is actually 7, so I changed that as well] ~~Six~~Seven of these pieces ~~are~~were retained to be used for the base of the puzzle. The user ~~will~~would be able to use this base as a reference when assembling the rest of the puzzle pieces. ~~The remaining 8 pieces are generated with up to 6 holes each for fitting the magnets. and up to 60 matching blind-holes distributed across the surface to fit the magnets.~~

4.4 Generating ~~matching blind-holes~~attachments both in the core and puzzle pieces

Once all puzzle pieces ~~have been~~were produced, ~~matching blind-holes~~it ~~is~~was necessary to generate attachments ~~which will~~to secure the puzzle pieces ~~to~~onto the core. Magnets are suitable attachments as they can be buried within the puzzle pieces and core. However, other female/male attachments are possible as well. In this step, the attachments for the Saltdean urn 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 8a.



(a) Cylinders generated using as input a set of points in 3D space

(b) Core with blind-holes across the surface

Fig. 8. Generating ~~of~~ matching holes for ~~fitting~~the magnets which ~~will be~~constitute the attachment mechanism for the Saltdean urn puzzle

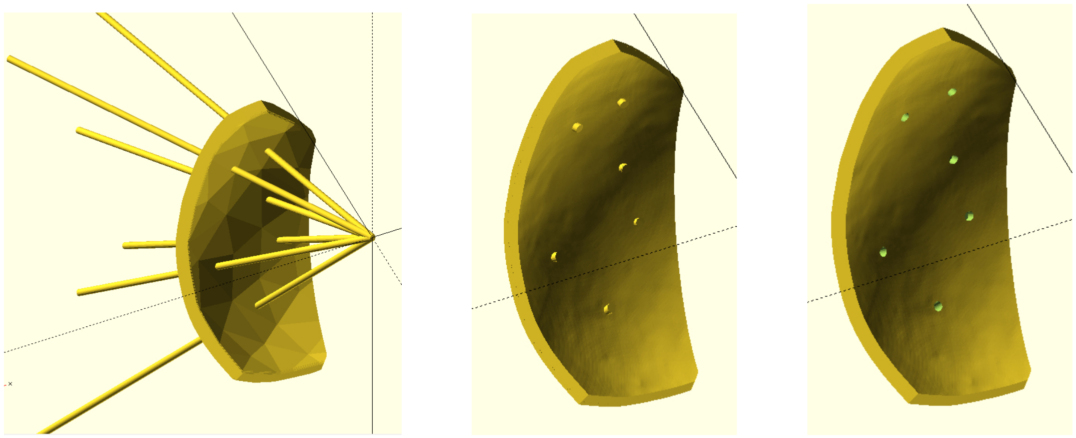
The algorithm to create the blind-holes is based on the intersection and difference operations. Hence, the algorithm can be described in Algorithm 1. This produces an intersection between the cylinder and ~~a simplified version of~~ the puzzle piece ~~for speed purposes~~as shown in figure 9a. It then 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 9b.

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;
3*dmodel*: 3D model of puzzle piece simplified;
thickness: thickness of the blind hole;
for $i \leftarrow 0$ **to** *length(points)* **do**
    point = points[i];
    unitvector = point/norm(point);
    translate($-unitvector * thickness$) intersection(3dmodel,cylinder($point.x$,$point.y$,$point.z$));
end

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

The generated geometries are then used to produce the blind-holes. This is achieved by using the difference operation between the 3D puzzle piece and the generated geometry (see Figure 9c). The same process is repeated for all ~~the~~ puzzle pieces ~~. This step produces all puzzle pieces with~~to produce the required blind holes (see Figure 1-c). MS [This figure is not relevant. Should we refer to 11a instead which shows all printed pieces?]

Furthermore, a similar process is repeated for generating the blind-holes in the central core piece using the same 3D points. However, this time the direction in which the intersected geometry is translated is reversed.



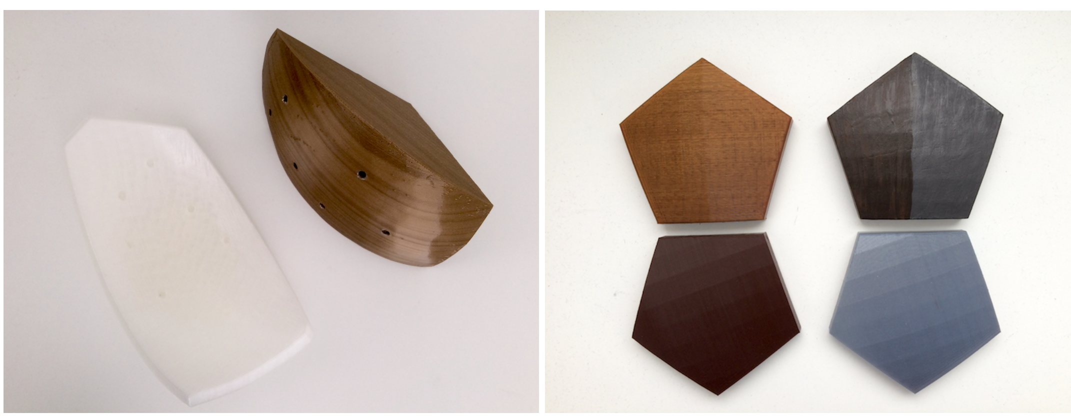
(a) Puzzle piece with cylinders for blind-holes

(b) Puzzle piece with geometry generated for the creation of each blind-hole

(c) Puzzle piece with blind-holes

Fig. 9. Generating blind holes for each puzzle piece

The resulting geometry is shown in Figure 8b. ~~The core also requires a through central hole for fixing it to the rotating base.~~



(a) 3D printed prototypes for validation

(b) Colour and texture for the puzzle pieces

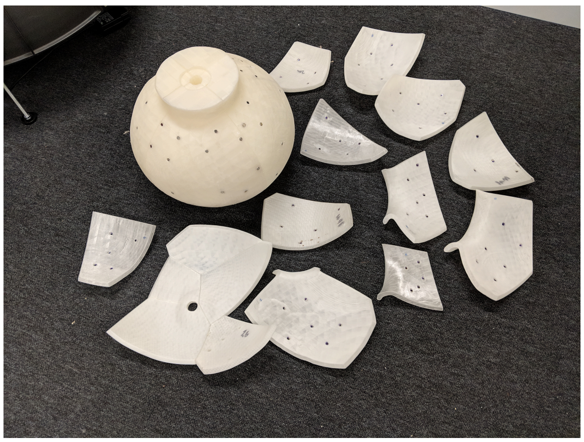
Fig. 10. Prototyping was performed before full fabrication of puzzle

4.5 3D printing puzzle pieces and core

~~Before printing all puzzle pieces,~~Before proceeding to fabricate the whole 3D puzzle, we undertook a prototyping phase. This has proven to be crucial in the overall design and fabrication process. ~~In this~~Hence, a sample set of pieces were 3D printed to validate the dimensions of the ~~holes~~design as well as to check whether the overall ~~dimensions~~measurements, infill density, material strength and weight were suitable for the ~~purposes of~~

~~the~~puzzle pot activity (see Figure 10a). Colours and textures were also tested (see Figure 10b). ~~Some minor~~Various adjustments were made to the dimensions of the ~~holes~~design to take into account tolerances caused by ~~other parts~~attaching printed pieces together and the layer thickness ~~printed layers for~~of the print. This thickness usually depends on the nozzle size and the machine and ~~will vary~~varies for different printing technologies.

Finally, all the puzzle pieces were 3D printed, as shown in Figure 11a. Although the core could be printed all at once, it was split into ~~eight~~four MS [Karina it was 4 pieces not 8] sections to achieve better printing quality (and less supporting material by allowing each section to be positioned flat on the printer's bed).



(a) Printed puzzle pieces and central core

(b) Post-processed puzzle pieces and central core

(c) Painting puzzle pieces and central core, photo courtesy of Russell Webb

(d) Painted and assembled puzzle at the museum gallery

Fig. 11. Fabricated puzzle pieces and central core generated by proposed workflow and final hands-on exhibit

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.

4.6 Post-processing all puzzle pieces and core

Post-processing of the puzzle pieces and the core ~~includes~~included removing the supporting material around the pieces and sanding any rough surfaces. Then, the magnets ~~are~~were inserted in holes at the back of each puzzle piece and on the core. The magnets that were considered as most suitable, after testing various types, were ø6mm x 4mm N52 high grade neodymium disk magnets with 1798g pull strength. ~~The holes are~~After placing the magnets in the core and puzzle pieces, the holes were covered ~~afterwards~~ with plaster and sanded accordingly.

When the plaster ~~has~~ dried, a coating using a mixture of PVA (Polyvinyl acetate) glue, marble powder, white acrylic colour which worked as a primer and water ~~is~~was applied on the puzzle pieces and core in order to provide a ceramic-like texture. Figure 11b ~~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.~~demonstrates the 3D puzzle assembled ~~once all the pieces and the core have been post-processed~~before the final post-processing steps. ~~Afterwards~~Finally, an artist painted the pieces ~~using the colours tested~~ to resemble the original pot and the core (see Figure 11c). Lines to provide clues about the shape of the puzzle pieces and facilitate assembly were also painted on the core. The final interactive exhibit ~~is~~was then placed at the museum gallery (see Figure 11d).

5 RESULTS

KR [need to add something here about the generalisation of the results. Tim can you advice?] MS [The text should also refer to figure 12 which demonstrates how the workflow can be deployed to accommodate additional shapes and types of artefacts in order to create further enjoyable educational museum experiences for young audiences without excluding other visitor groups.]

6 EVALUATION

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

The detailed 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~~be presented in the future ~~once the Gallery is open to the public~~as part of a larger research project on digitally fabricated interpretation material. A detailed method for the evaluation of the overall experience has already been set up and tested with another artefact and museum [26].

However, since the puzzle activity has already been installed and visitors are interacting with it at the Archaeology Gallery, some initial remarks have been made. These relate mostly to the access that people have to the exhibit and their motivation to spend time with it. Hence, we have found that the rotation of the core and base facilitates assembling the puzzle, nonetheless having full 360-degree physical access to the spot might allow groups of people to interact with it in a more easy and comfortable way. As for the space where the puzzle pieces rest, it is better to have a kind of tray or physical barrier in order to prevent pieces from falling down and possibly brake. Lastly, it has been noticed that visitors are more willing to try the activity when they find the puzzle unassembled and its pieces lying around the core, instead of seeing the fragmented pot already put together.

MS [I believe that the following comparison to other methods should be placed in the discussion section or even in the results, but not in the evaluation] A final consideration is given to how ~~this~~the proposed solution compares to

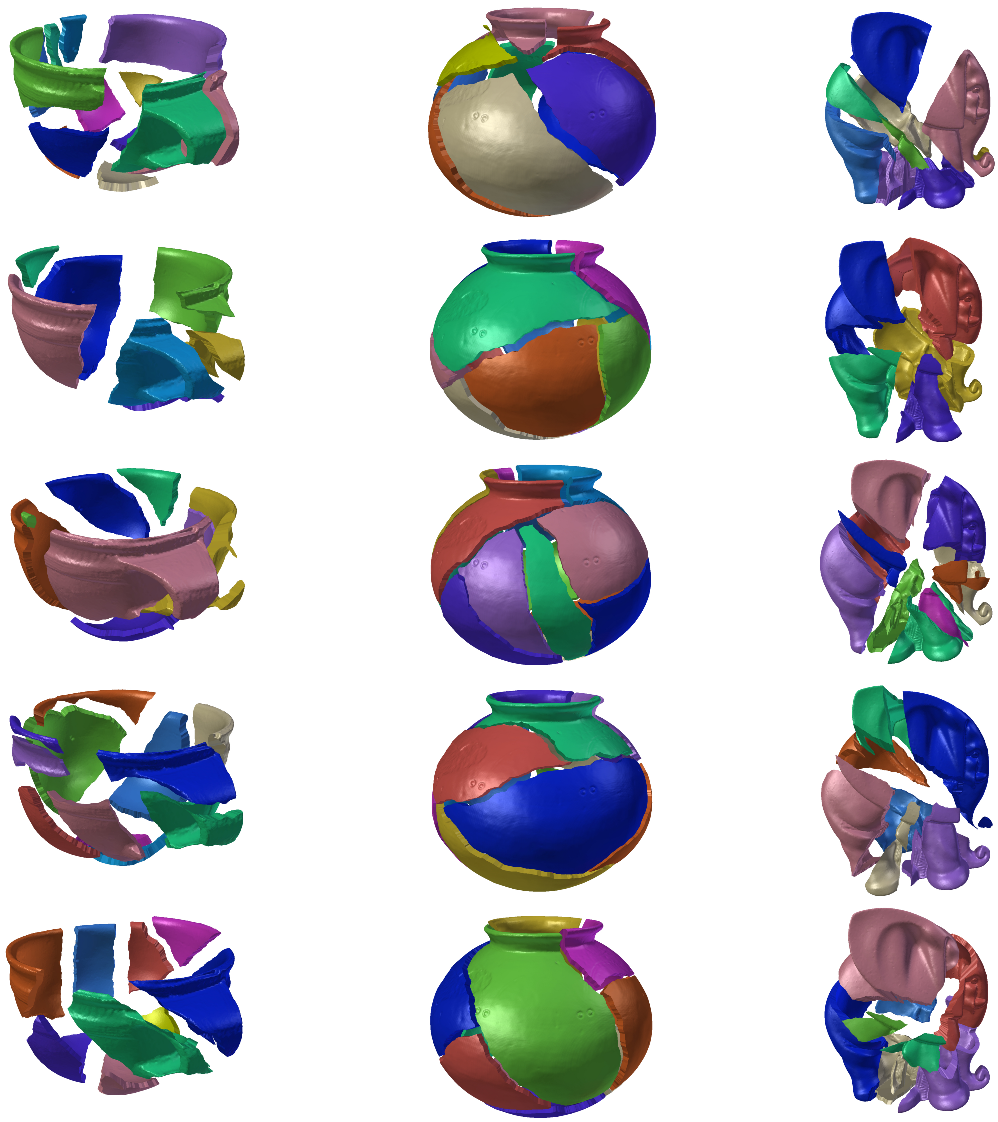
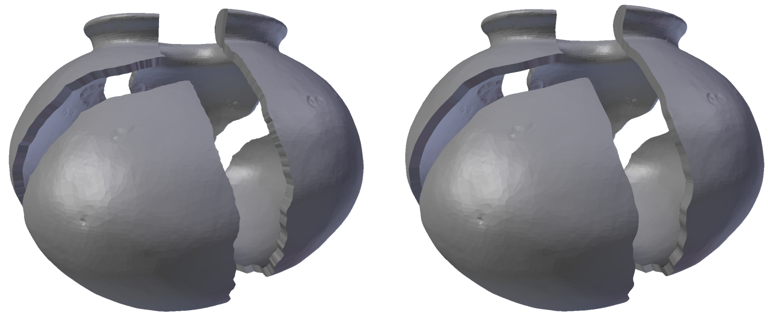


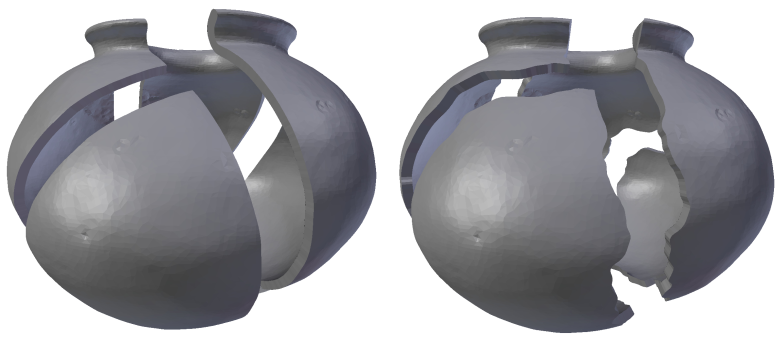
Fig. 12. Examples of algorithm applied to scans of an amber cup, Saltdean pot and ceramic elephant figurine.

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 and a core could ~~then~~ be made (even though producing a core should be a rather demanding task). ~~This~~The whole process ~~is not~~would not be 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



(a) m: 6, niter: 6, jitter: 0.3, amplitude: 0.1, decay: 0.5, smoothing: 0.0

(b) m: 6, niter: 6, jitter: 0.3, amplitude: 0.1, decay: 0.5, smoothing: 1.0



(c) m: 6, niter: 6, jitter: 0.3, amplitude: 0.01, decay: 0.5, smoothing: 0.0

(d) m: 6, niter: 6, jitter: 0.3, amplitude: 0.2, decay: 0.2, smoothing: 1.0t

Fig. 13. Examples of puzzles with different parameters

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~~have to be 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~~would 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.

7 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~~is part of the Archaeology Gallery 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". We ~~then~~also explore alternative fracture patterns in order to generate different types of puzzle pieces. An algorithm is then proposed to generate the puzzle fragments or shards and the attachments, such as 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.~~

KR [we need to rephrase this, as I don't think these really are the greatest challenges.... the challenge really is the fabrication.] MS [Karina I have added the following, please rephrase it as you wish]

~~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.~~Some of the challenges that we experienced and could be faced when creating similar puzzle activities are related to the creation of a watertight mesh out of a partially scanned pottery artefact. Another challenge is the selection of the right fragmentation pattern in order to comply with the design requirements. However, the biggest challenge is related to the fabrication of the puzzle pieces and core as tolerances due to the layer size of the 3D printing technology as well as post-processing steps (e.g. pasting pieces together, using certain materials) might greatly affect the final appearance and functionality of the exhibit. That is why prototyping and iterative testing is crucial, in order to understand how measurements, settings and processes might need to change in order to successfully produce a satisfying result.

To conclude, we argue that 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.

8 ACKNOWLEDGMENTS

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