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SEMIAUTOMATIC FRAGMENTS MATCHING AND VIRTUAL RECONSTRUCTION: A CASE STUDY ON CERAMICS

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Abstract

Artefacts' reconstruction is a fundamental part of conservation and one of the most common remedial conservation activities with great contribution to archaeological research. The manual procedure for fragments' matching is a painstaking, time- and space-consuming operation. As a result the development of working methodologies for digital refitting of fragments is of fundamental importance for archaeological research and conservation practice. This study presents a comparative analysis of manual and digital reconstruction, which has never been explored even if computer scientists have achieved many developments in the field of digital refitting. Results indicate the parallels between manual and digital processes in terms of durability, integrity and practicality. Also, in order to provide methodological directions to conservators, three different semi-automatic fragments matching approaches based on their effectiveness in managing the project and alignment of fragments were used A combined strategy, making use of different pieces of software, is recommended. In addition, the modelling techniques for digital restoration were described along with the uses of the virtually restored artefact. Faenza maiolica, black-glazed, Gnathian and coarse ware ceramics were used as case studies.

Keywords: *Digital refitting; Virtual reconstruction; Digital restoration; Fragments' matching*

Introduction

It is common for archaeological material to survive in a deteriorated condition, fragmented and incomplete. A fracture may have taken place intentionally in antiquity, at a time when the object was destroyed due to not being useful anymore, or unintentionally, for example because of physical disasters, or as a result of normal material degradation during burial. Apart from the ancient fractures, objects may break during excavation or transportation to the museum, considering the changes introduced to the artefacts' environment by excavation and the human factor as an agent of deterioration. An object in fragmentary state should be reconstructed, making this process one of the most common remedial conservation activities. There is no doubt that reconstruction is a fundamental part of conservation, and its contribution to archaeological research is of great significance. It throws light on the interpretation of the archaeological site, the determination of its use and the technology of our ancestors. Hence, researchers aim to develop methods, able to efficiently deal with fragments matching problems complexity.

The conventional methodology is based on excavation data, previous knowledge about known artefacts types, decorative elements, and evidence of manufacture, degradation pattern,

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geometry, volume and texture of the fragments [1]. This manual procedure is a painstaking, time- and space-consuming operation, even for dedicated, experienced professionals. Manual search provides sufficiently effective results when the number of fragments is reasonable and the overall condition of the material permits excessive manual handling. In cases with large groups of fragments the results are rather disappointing, considering the time and expertise needed. Further complexity is introduced by the missing fragments.

In an attempt to provide solution to this problem, computer-aided reconstruction of archaeological objects has been proposed for a variety of material, such as pottery, architectural stone fragments and wall paintings [2-7]. Another area worth considering is the work of forensic science in documents reconstruction [8-9]. Methods used were focused on surface intrinsic characteristics, geometric information, surface texture and pictorial data, typology, volumetric models and fracture curves [10-15].

Nevertheless, the proposed methodologies do not meet the needs of conservation. Archaeological fragments digital refitting is a complex signal processing problem, because of the nature of archaeological material, with its particular characteristics, such as the unknown original shape, the presence of gaps of various sizes, the non-uniform surface deterioration and the complex three-dimensionality of objects. Due to this fact the level of expertise required for the practical implementation of digital refitting goes beyond the field of conservation and the computational cost is still high. An intermediate approach, between digital and manual methodologies, is the semiautomatic fragments matching using 3d software, such as MeshLab and 3ds max. The latter is a powerful 3d design software which provides comprehensive modelling, animation, simulation and rendering solutions. Max script programming language provides automatization, which might be useful for fragments matching [16]. MeshLab is an advanced mesh processing system for automatic and user assisted editing, cleaning, filtering and converting and rendering of large unstructured 3D triangular meshes [17]. Fragment Reassembler, a computer-assisted method for virtual reassembly of fragmented objects, was developed at Visual Computing Laboratory - ISTI – CNR. The software finds the best match between two fragments based on constraints given by the user, using a global energy minimization that considers all the pieces involved in the reconstruction process at once. It is based on a hierarchical system, where two fragments matched form a group, to which a third fragment or group of fragments can be attached. The user can move/transform the initial points, offering the opportunity to align fragments, even if they are severely damaged or eroded [18-19]. Beyond fragments matching the 3d digitised artefacts can lead to virtual reconstruction using 3d modelling techniques. This methodology has been proposed in various cases, such as those involving extreme dimensions and weight, or fragile, unstable, complex artefacts, whose restoration presents technological problems or raises ethical issues [20-25].

This study presents a comparative analysis of the three pieces of software, based on their effectiveness in managing the project and alignment of fragments, having as a main goal to provide the best strategy for semiautomatic fragments matching. In addition, the manual and semiautomatic fragments matching approaches are compared with a particular emphasis at the contribution on conservation objectives. Then, the available options for virtual reconstruction using photorealistic and non-photorealistic rendering techniques are demonstrated.

Study material

Fragments of two similar late medieval maiolica, probably from Faenza, with medallions on the front depicting piscine zoomorphic designs painted with blue and orange mineral pigments on a tin-glazed opaque background [26], were used as a case study for the comparative analysis of different fragments matching approaches (**Fig. 1**). For the demonstration of digital restoration an incomplete black-glazed chous, a Gnathian skyphos and a coarse ware ceramic fragment from a neopunic amphora, from the archaeological Collection of the University of Southampton were used as case studies (**Fig. 2**).

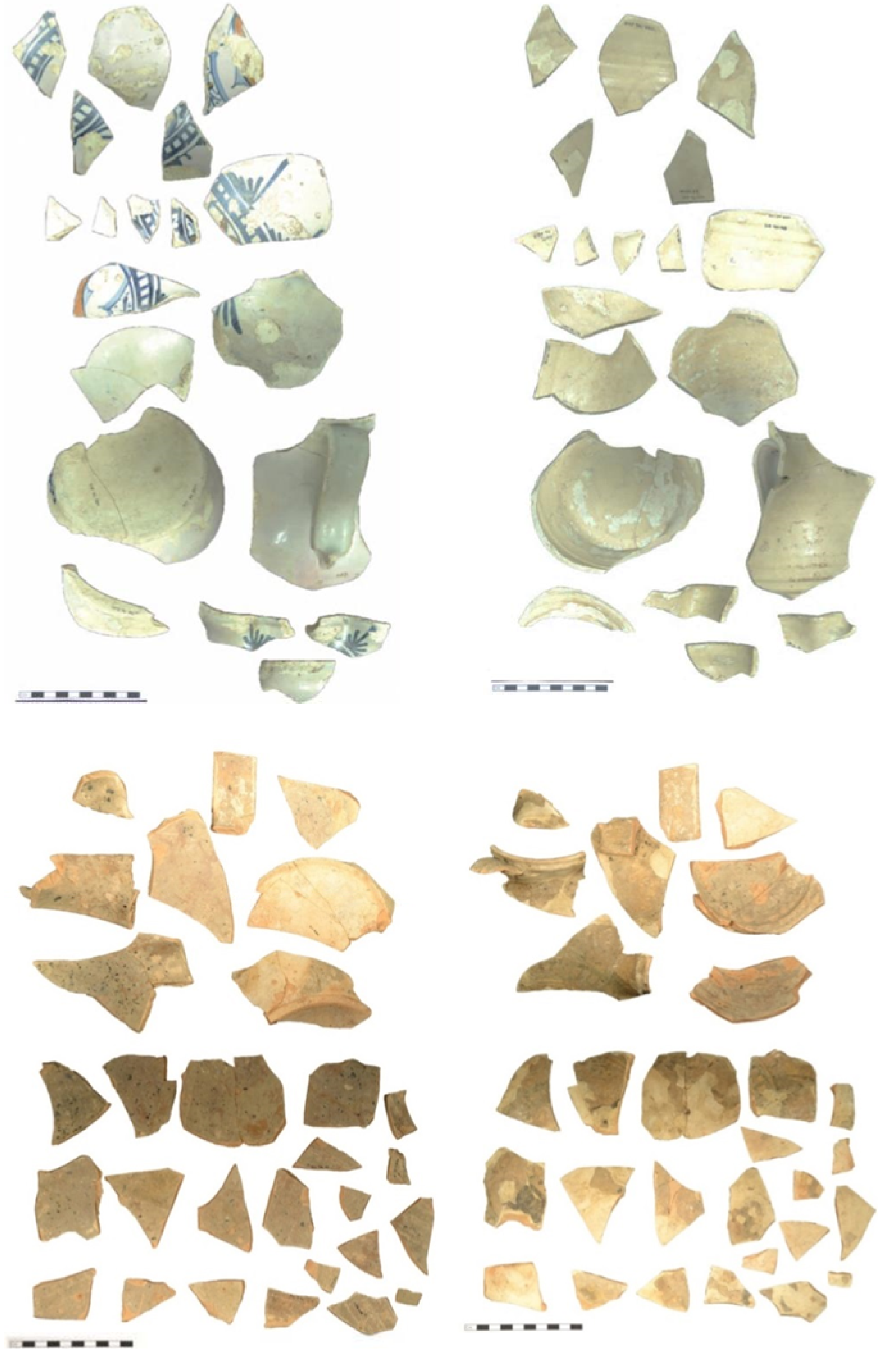

Fig. 1. North Italian Sgraffito jug fragments in Faenza Maiolica. Southampton City Council, Arts & Leisure. No 366 (Fabric 1450- SOU 124 176), outside (above left) and inside (above right). No 367 (Fabric 1450- SOU 128 43), outside (below left) and inside (below right).

Fig. 2. Ceramics used as case studies for digital restoration, from left to right, an incomplete black-glazed chous, a Gnathian skyphos, and a coarse ware ceramic fragment from a neopunic amphora, from the archaeological Collection of the University of Southampton.

Experimental part

Manual fragments matching

The manual fragments matching operation was video recorded and video transcripts have been produced in order not only to analyse the whole procedure and the individual actions that took place, but also to be used as guides for the digital fragments matching.

3D digitization

CT was chosen as the appropriate 3d digitization strategy for the maiolica ceramics as it does not only succeeds in capturing the volume but also offers the opportunity to study the internal structure of the ceramics [27]. The amphora fragment and the vessels were photogrammetrically reconstructed using the Agisoft Photoscan software [28].

Virtual reconstruction

For the semiautomatic fragments matching three different pieces of software, MeshLab, Fragments Reassembler and 3ds Max were employed. The latter was also used for the virtual restoration.

Open Provenance Graph

Open Provenance Model (OPM) [29] was used in order to explain and describe the processes in which digital data and things with a physical existence have been involved during the semiautomatic fragments matching.

Results and discussion

Comparative analysis of semi-automatic fragments matching software

The three pieces of software were examined based on their effectiveness in managing the project and alignment of fragments. In 3ds Max managing the digital refitting project, where each object in the scene represents a pottery sherd, is easy because of the use of summary statistics and scene explorer. These features display statistics and provide useful information about the current scene, meaning the number of objects, the total vertices and faces of mesh. The objects can be sorted in a list by category and object name, assigned material name, and type of material, object vertex and face counts. Further options for sorting, filtering, and selecting objects, as well as additional functionality for renaming, deleting, hiding, and freezing objects, as well as creating and modifying object hierarchies are provided by the Scene Explorer. In MeshLab the layer dialog enables managing the scene, where each fragment appears in its own layer and transformation matrix. In Fragments Reassembler the graph modification area is designed so as to manage the digital refitting project. 3ds Max is the most powerful software in terms of managing the project, because of the advanced options provided for selection, grouping and viewing the fragments. Similar capabilities, although with less functionality, exist in MeshLab. Fragments Reassembler proved to be the least useful in managing the project.

For the alignment of fragments the tool specially developed for these operations, Fragments Reassembler, proved to be the most efficient, although practical problems occur in the reconstruction process, mainly because the software is still in beta version, an early stage of development. A similar result can be achieved using MeshLab, but the whole process is much more time consuming and limited to well-preserved fragments. It is highly unlikely to achieve the same or a similar result using 3ds Max, because of the limited functionality of the alignment tools provided. It is worth mentioning that MeshLab and Fragments Reassembler are open source while the 3ds max software is commercial. Moreover, the advanced options provided by the latter require in-depth knowledge and familiarity with 3d software.

In MeshLab the user identifies one fragment of the fixed mesh as the base of the reconstruction and a second fragment as a moving mesh. At least 4 pairs of points, given by the user, provide the necessary information for the algorithm to find the best rigid transformation that bring the points of Moving mesh onto the corresponding points on the Fixed mesh (**Fig. 3**).

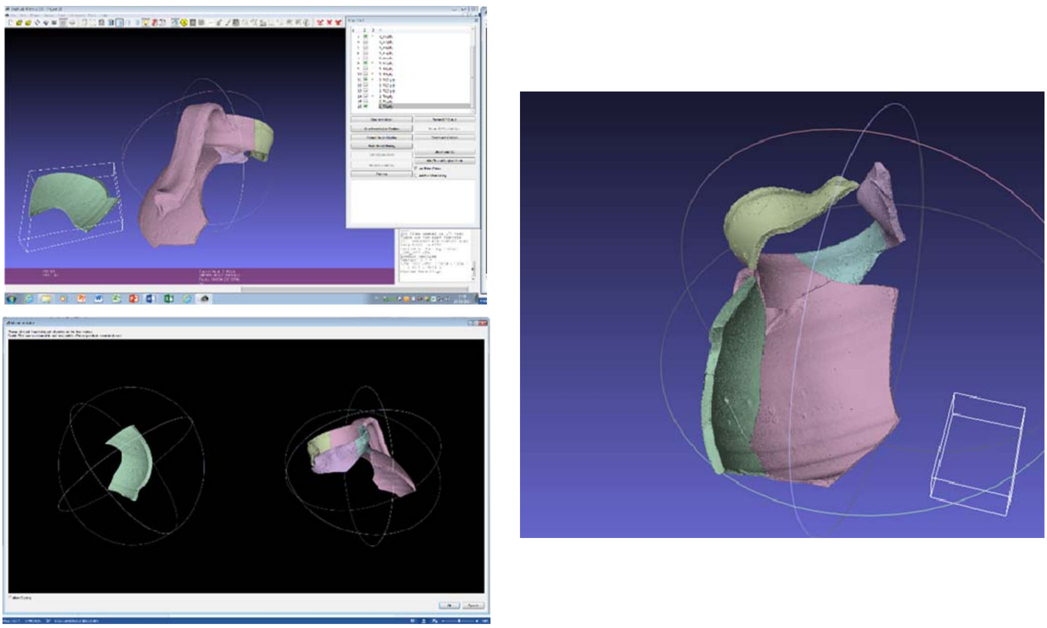

Fig. 3. Using the align tool in MeshLab.

Although, in theory, this process is feasible, and all fragments can be aligned successively over those already aligned, in practice this semiautomatic reconstruction operation is problematic. First, this process is not flexible. The user cannot modify the points of joins, and the procedure should be repeated from the beginning if a pair of points is given by mistake. Second, this method is inefficient in case of voids between fragments, whether they are larger or smaller. This is a significant disadvantage, particularly in cases of worn edges, which is almost always the case with archaeological fragments. Third, it is difficult to take into consideration the colour of the fragments and the painted designs, because the align tool does not enable the visualization of materials. Fourth, in the case of large number of fragments and/or high resolution meshes, the processing time becomes longer and technical problems arise. In order to overcome these problems, the best option is to create groups of fragments, flatten the meshes, export them as one file and proceed to the reconstruction having a significantly reduced number of fragments.

The alignment of the fragments using the available 3ds Max tool proved problematic. Precise positioning of a fragment relative to another is difficult. The options provided by max script offered advanced functionality in moving and rotating objects. In case of actions that have been already scripted, such as the arrangement according to size, max script proved to be particularly useful (**Fig. 4**). The main disadvantage is that complicated actions, such as the matching of fragments, are difficult to execute because the necessary scripts are not developed yet. The comparative analysis of the three approaches assessed in the semiautomatic fragments matching is summarised in **Table 1**.

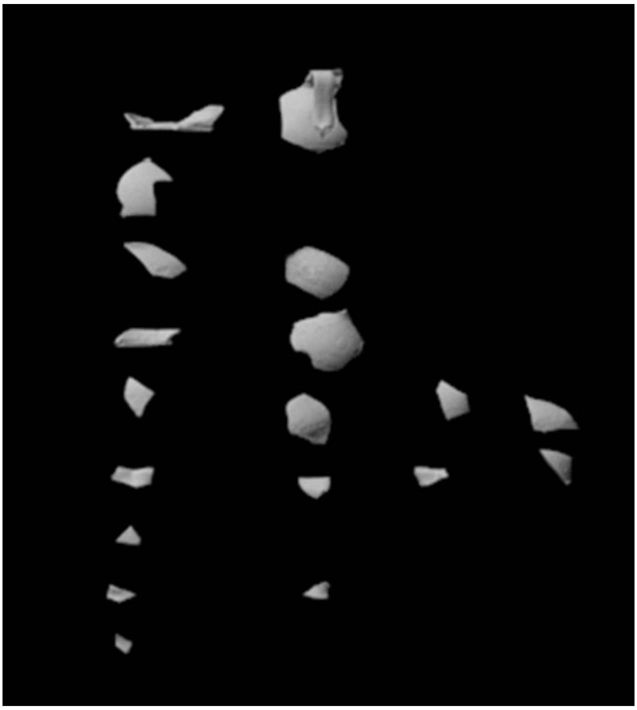

Fig. 4. Alignment and distribution of fragments in 3ds max using max script.

Table 1. Comparative analysis of software used for the semiautomatic digital refitting

Software	Managing the project	Alignment of fragments	Advantages	Disadvantages
3ds Max	High functionality	Inefficient	Advanced options for managing the project Powerful tool for virtual reconstruction	Expensive Difficult to use Requires high computational power
MeshLab	Medium functionality	Medium efficiency	Free Medium efficiency in aligning damaged fragments Efficient in aligning well preserved fragments	Difficult to use for non-experienced users
Fragments Reassembler	Low functionality	Efficient	Free Efficient in aligning fragments Easy to use	Limited functionality in managing the project Only useful for alignment In development stage-beta version-problems in use

Manual fragments matching case study: Jug No 366

From the 17 shreds, attributed to jug No 366 only one remains unidentified and there is no doubt that it belongs to another pot. Fragments of the lower part of the body are missing as well as small fragments of the base and the rim. From the careful observation of the videos, transcript in excel was created which enable the quantitative analysis of the project. The actions executed during manual fragments matching were the following: 1) observation, 2) selection of fragments with possible joins, 3) testing joins, 4) matching fragments and 5) securing joins temporarily. Along with instinct choices, the criteria used for manual fragments matching during the selection of the fragments were 1) the shape, 2) the painted design/ colour, 3) the texture and 4) the texture and shape. Almost half of the actions involved in the project were relevant to testing for joins, while the occurrence of other actions is significantly lower. 60% of the successful matches were found based on shape, followed by 20% based on painted design. Other parameters lead to fewer matches and were mainly employed in case of repetitive unsuccessful tests (**Fig. 5.**). In **Figure 6**, the vertical axis represents the tests executed during searching for matches. The horizontal axis shows the criteria used. The red and blue bars depict tests resulting in successful and unsuccessful matches respectively. In both cases this comparison reveals that shape of fragments was the most frequently used criterion for searching as well as the most efficient one.

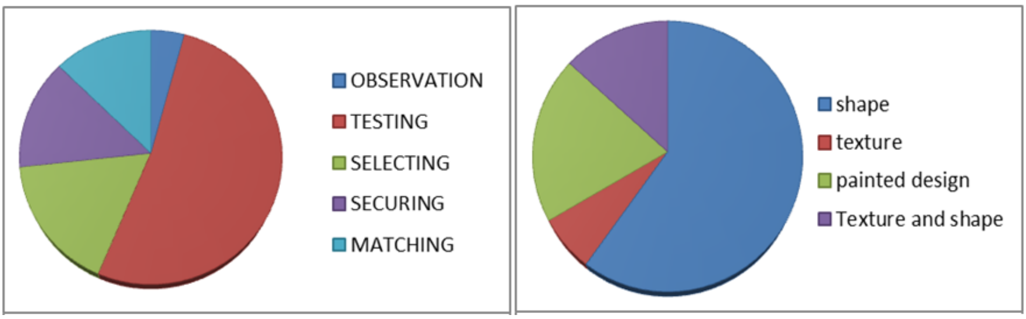

Fig. 5. Contribution of each criterion in successful matching of fragments (above) and occurrence of actions involved in the manual fragments' matching.

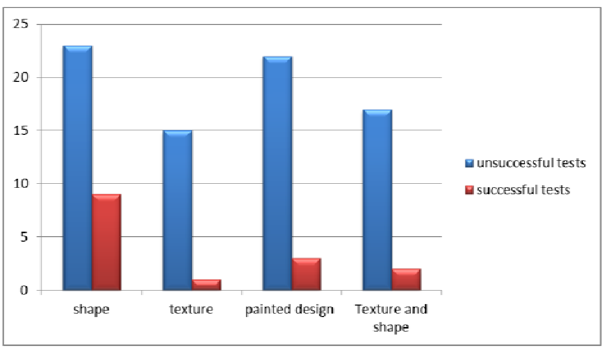

Fig. 6. Number of unsuccessful tests and successful matches for each criterion.

Semi-automatic fragments matching case study: Jug No 367

The results of the comparative analysis of semiautomatic fragments matching were valuable for the reconstruction of jug No 367, whose fragments had not been identified manually. The digitised fragments were imported to 3ds Max, making use of the advanced option for managing the project and then the alignment were executed using Fragments Reassembler.

The 28 fragments attributed to jug No 367 were imported to 3ds Max and using the measure utility the total volume was calculated. Then the volume was compared to the estimated volume of a complete pot of similar type, leading to the conclusion that almost 30 % of the vessel's volume is missing. By estimating the amount of missing material of the ceramic vessel, the conservator can gain a better understanding of the expected outcome of the reconstruction. The fragments were also grouped based on their shape using max script. This initial categorization concerns mainly larger fragments because these were more likely to be attributed to a specific type based on their shape. Based on this grouping the fragments were categorised in to five groups, three fragments from the base, two fragments from the rim, two fragments of the handle, three fragments of the upper body and one fragment of the body (**Table 2**).

Table 2. The fragments from the Jug listed according to their volume in metric units, and attributed to a specific type based on their shape.

Name	Volume	Description
367_2_R4	39209.72	base
367_3_R1	32322.59	rim
367_3_R2	30902.19	handle
367_3_R3	28381.16	base
367_4_R1	26569.53	rim
367_2_R3	24715.29	body
367_2_R1	15491.53	handle
367_3_R4	14674.85	upper body
367_3_R6	14243.9	upper body
367_1_R17	13697.6	upper body
367_4_R3	10656.04	base
367_2_R2	9235.91	body
367_4_R2	8801.76	body
367_3_R5	8061.05	body
367_1_R16	7839.36	body
367_1_R2	6815.4	rim
367_1_R8	6365.28	body
367_1_R10	5369.21	body
367_1_R15	5028.26	body
367_1_R1	4699.66	rim
367_1_R7	4668.8	body
367_1_R3	3501.84	body
367_1_R4	3386.9	body
367_1_R6	3154.76	body
367_1_R12	1794.13	body
367_1_R5	1733.35	body
367_1_R11	1523.22	body
367_1_R14	875.53	body

The selected fragments were aligned based on their geometry-shape, colour, and ceramic wheel marks leading to the construction of 5 groups; fragments of the body, the base, the rim, the handle and the upper body (**Fig. 7 and 8**). The alignment was executed in Fragments Reassembler. One of the remaining smaller fragments is part of the rim while the others were attributed to the body of the vessel. The virtual matching of these groups of joined fragments leads to the virtual reconstruction of the pot as shown in **Fig. 9**. The curvature and profile assisted the correct positioning of the remaining fragments, apart from two fragments, which were not identified, probable due to their severely damaged edges. An Open Provenance Graph describes the process for semiautomatic fragments matching (**Fig. 10.**). The findings of the virtual reconstruction were assessed physically following the traditional manual methodology, resulting in exactly the same fragments' identification.

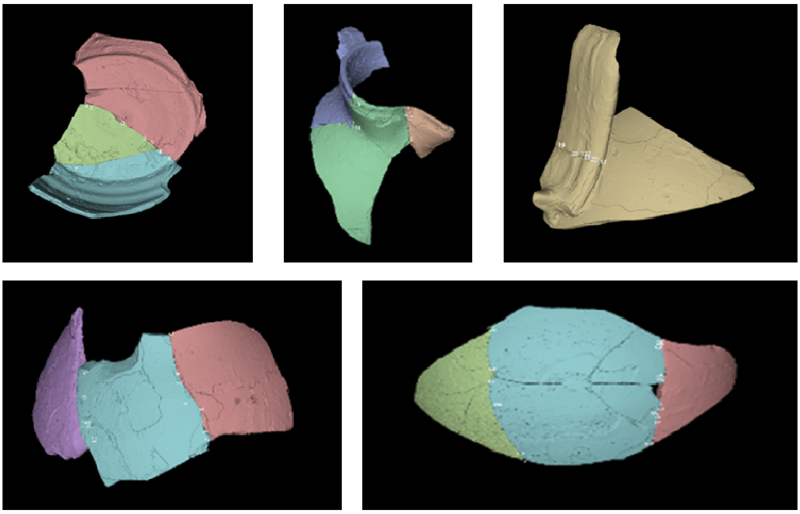

Fig. 7. Screenshots of Fragments Reassembler, clockwise from top left, pParts of the base, the rim, the handle and the body.

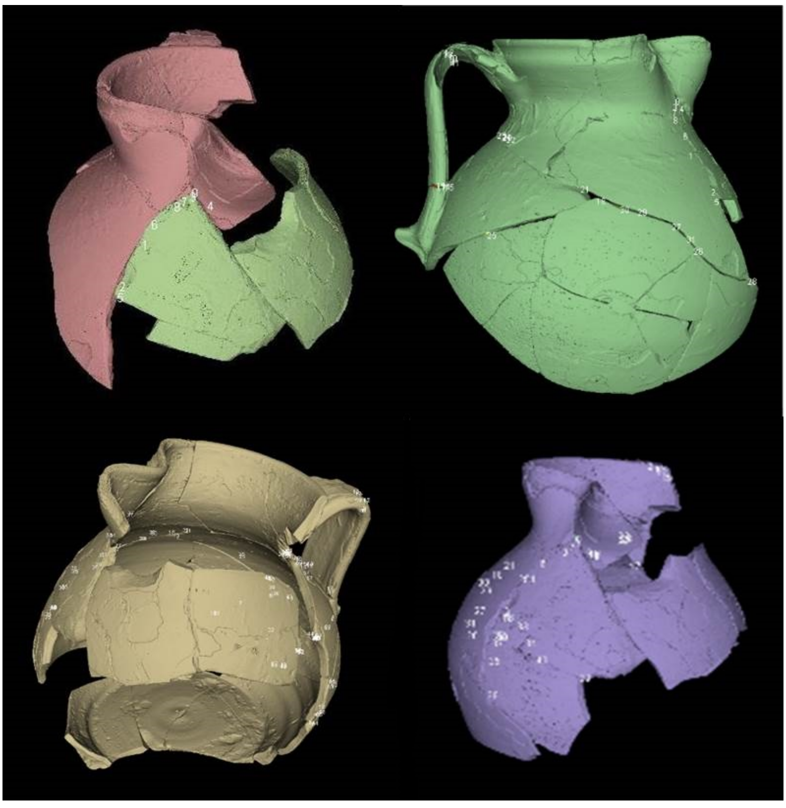

Fig. 8. Virtual reassembly of the groups in Fragments Reassembler, clockwise from top left, matching fragments of the rim and the upper body, matching fragments of the lower body, matching remaining fragments of the body and final reconstruction.

Fig. 9. Virtual reconstruction of gnathian skyphos. Non-photorealistic rendering created in 3ds Max. The new additions were rendered in red, yellow and green.

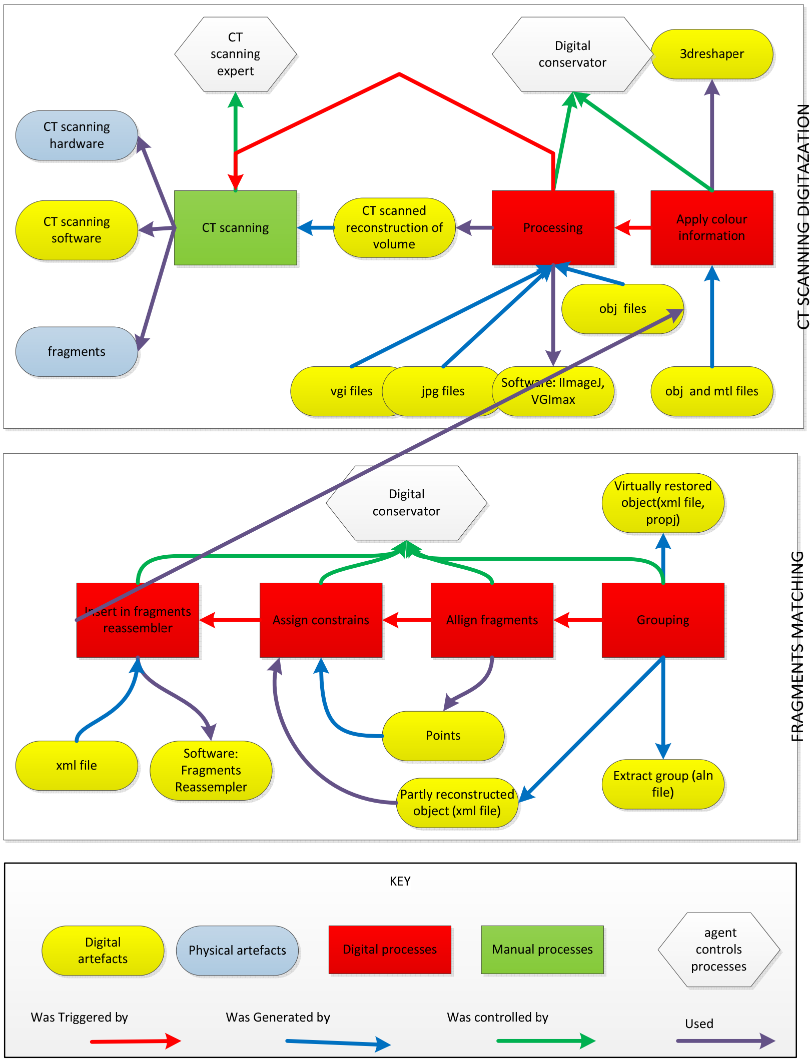

Fig. 10. Open Provenance Graph for semiautomatic fragments matching

Comparative analysis of manual and semiautomatic fragments matching

The fragments matching, as a core conservation operation, made the artefacts more accessible and understandable, whether it was executed physically or in a virtual environment, although the processes differ from a methodological perspective. An analysis of the semi-automatic and manual fragments matching reveals the parallels in terms of durability, integrity and practicality. There is an analogue here between the practical problems that arise in physical and virtual worlds. The problems of fragility and extreme dimensions have been discussed in the literature in cases of reconstruction of material in poor states of preservation, highly fragmented and/or large architectural parts. These problems govern the methodological approach and negatively influence the outcomes of the process. Although digital restoration provides a solution, the practicalities of digital refitting are similarly problematic. The computational power required for digital refitting of high resolution 3d digitised fragments, especially when a large number of fragments are considered, is high and slows down the process considerably. There is a need to compromise, reducing the resolution in order to overcome software and hardware constraints.

From a preventive conservation perspective the manual approach provides limited flexibility to the conservator. In particular complex reconstruction operations might cause risks to the material. Managing risks in interventive treatment is more demanding than managing the risks of 3d digitisation. In addition, the long-term structural and chemical integrity of the reconstructed object, compared to the digital preservation of the replica (either digital or physical-3d printed one), is more unpredictable. Hence, the digital reconstruction is advantageous from a strictly preservation or prevention point of view. Similarly, the digital approach is preferable for communication purposes. 3d models and audio-visual material from the digital execution of fragments matching operation can be disseminated easier for publication, documentation, training and outreach.

Virtual restoration

3d modelling can assist the physical restoration in a number of ways. First, the digitally restored model can support the treatment proposal. Second, there is no need for extensive physical interaction with the fragments, considering that the exact positioning of each fragment is known. Third, using simple 3d modelling tools, a model of the inside of the object can be created and 3d printed in transparent material. This can act as a support for the positioning of the fragments, assist in the organisation of fragments and also allow the use of less quantity of adhesives for gluing. Fourth, the missing parts can be modelled and 3d printed in an attempt to enhance the physical restoration of the object. For example the non-photorealistic rendering of the virtually restored skyphos shown in Fig. 7, can be useful for treatment proposals and documentation, as it emphasizes the new additions. Beyond documentation, virtual reconstruction assists in case of difficult remedial conservation operations. In the case of the amphora the physical restoration would be time-consuming because of the size and the large area that needs to be restored. After classification of the fragment, via 3d modelling, the missing area can be designed so as to match the geometry of the original ceramic material. In case of symmetrical features, such as the handles, replication is extremely easy in 3d software. By applying an appropriate material to the replicated part, the final virtual reconstruction, shown in **Fig. 11**, represents the object as if it has been physically restored. In the case of the chous, the missing handle can be virtually attached to the incomplete vessel via 3d modelling. In order to represent the chous as if it was complete not only the geometry but also the materials need to be reconstructed. This process is similar to conventional restoration operation, but easier to execute. The material of the body was replicated and applied to the handle, resulting in the final digital restoration of the chous (**Fig. 12**).

Fig. 11. Virtual reconstruction of the amphora, rendered as if it was restored in 3ds Max.

Fig. 12. Virtually restored chous, rendered as if it was complete in 3ds Max .

3D digitization

Although the determination of composition and provenance goes beyond the scope of the present study, the capabilities of CT in this area of research should be noted. The dataset will be further analysed in the future, but the most interesting findings will be briefly discussed. The morphological study of the vessel's handle reveals a large void. This finding provides an insight into the manufacture and forming of the vessel. It would have been impossible to acquire this information non-destructively. In addition the CT scanned fragments can be rendered using volume rendering techniques that afford the opportunity to expose different parts of their volume, by modifying the opacity. The Phong renderer presents the object as solid. The isosurface presents the object as if the ceramic material is less dense, emphasising the volume of the glaze. The volume renderer scatter presents the glaze as if it is translucent. Details, such as the preservation of the glaze and cracks, can be examined in detail (**Fig. 13**).

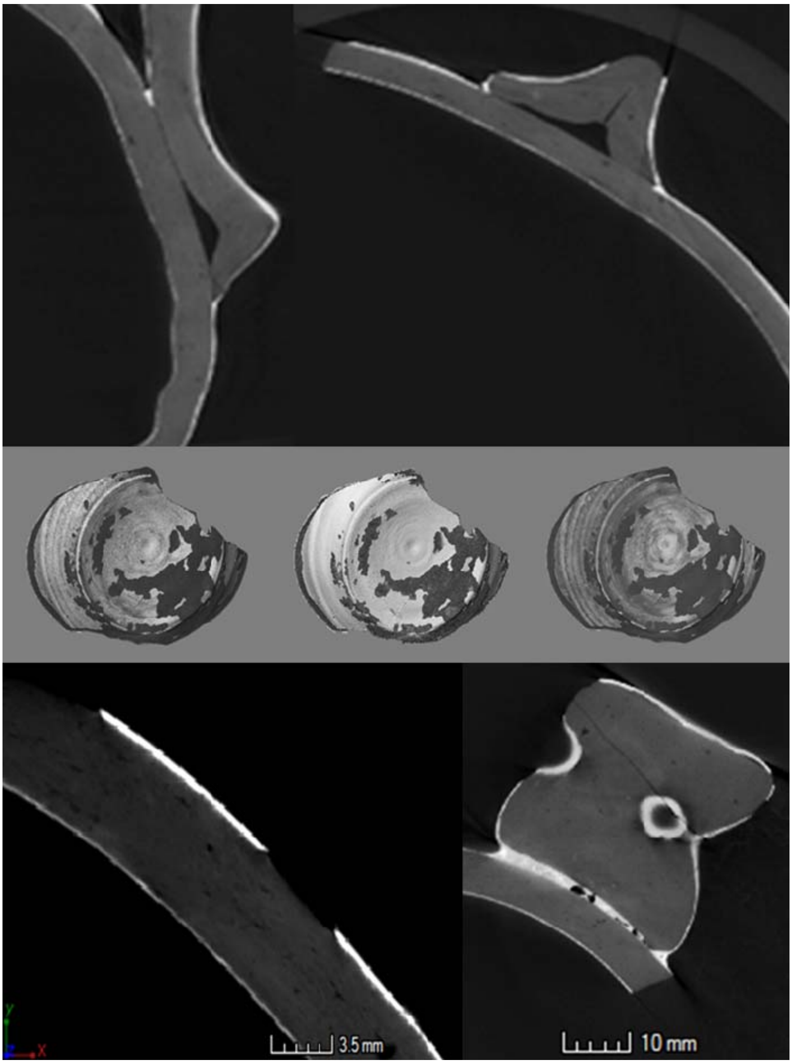

Fig. 5. CT scan renderings VG Studio max, horizontal sections of the handle (above left) vertical sections of the handle in (above right), Phong rendering of the base (middle left), Isosurface (middle), Volume renderer scatter (middle right), details showing the preservation of the glaze (below left) and cracks.

Conclusion

Three different semiautomatic fragments matching approaches were compared to each other as well as to manual procedures. For successful semiautomatic fragments matching a combined strategy is proposed. First the use of 3d software for managerial purposes as well as for metric calculations and initial categorisation of fragments is recommended. Second, the use of Fragments Reassembler proved to be the most efficient approach for the alignment of fragments. The proposed methodology secures the overall successful execution of semiautomatic reconstruction, providing the best results in terms of alignment with time efficiency. Open Provenance Graphs were used to represent graphically the processes that take place, the physical and the digital components that are either used or generated. Although their contribution is vital in the area of documentation, the Open Provenance Graphs can act as guidelines for the appropriate implementation of methodologies proposed.

The manual and the virtual reconstruction processes were compared in terms of conservation objectives and the similarities as well as the differences were analysed. Apart from accessibility, the contribution of virtual and physical reconstruction differs in integrity, durability and practicality. The digital preservation and the software and hardware constrains are among the most problematic aspects of the digital reconstruction. On the other hand, the advanced options for documentation provided by further processing of virtually aligned fragments or incomplete vessels enhance the conservation methodology.

Acknowledgements

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