Develoment of an Integrated Method for Reassembly Fragmented Objects

Amit Chandrakar
LS2N, Ecole Centrale de Nantes
1 Rue de la Noe, 44300
Nantes, France
amit.chandrakar@eleves.ec-nantes.fr

*Yicha Zhang
LS2N, Ecole Centrale de Nantes
1 Rue de la Noe, 44300
Nantes, France
yicha.zhang@irccyn.ec-nantes.fr

Florent Laroche
LS2N, Ecole Centrale de Nantes
1 Rue de la Noe, 44300
Nantes, France
florent.laroche@irccyn.ec-nantes.fr

Alain Bernard
LS2N, Ecole Centrale de Nantes
1 Rue de la Noe, 44300
Nantes, France
alain.bernard@irccyn.ec-nantes.fr

***Résumé*—In some application domains, repairing relics, joining broken bones in medical surgery, etc., reassembly of fragmented objects is required. Much research was conducted to reconstruct 3D virtual or physical full prototype models as 3D references for supporting the repairing or reassembling process. However, very little attention was paid to the reassembly sequence and operation. To obtain a good reassembly result as well as to reduce damage risk and save assembly time, the reassembly sequence and the assembly operation should be studied. Based on this point, this paper proposes an integrated method which uses both virtual and physical prototyping techs with allied tools for solving the reassembly problem with higher efficiency and better quality. A part of the implementation work is presented to demonstrate the potentials of the proposed method.**

***Mots-clés*—Fragmented object, Reassembly, Virtual prototyping, Additive Manufacturing**

I. INTRODUCTION

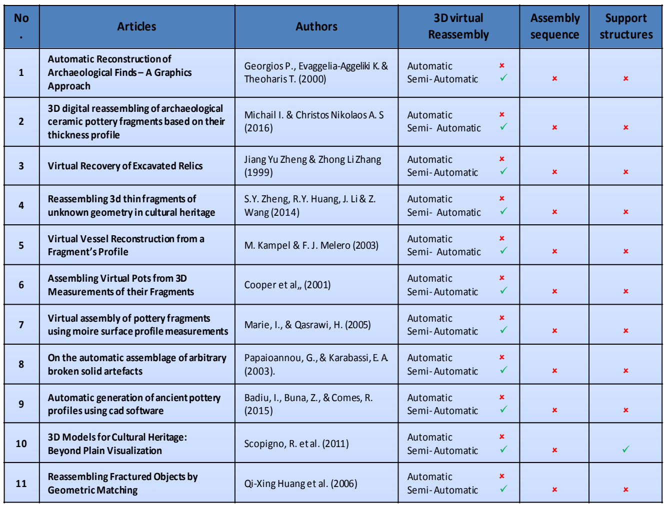
Plenty of research activities have been carried out to obtain 3D virtual or physical full models of broken objects by using digitizing 3D modeling and additive manufacturing methods so as to aid the repairing process. These obtained 3D virtual or physical prototype models of fragmented objects could be good 3D references for the reassembling or repairing process. However, when the number of fragments is large and the assembly environment is complex with extra constraints, e.g. in surgical operation context where constraints on working space and assembly time exist, then the reassembly process becomes more complicated and even NP-hard. Current practice, mainly manual trial and error method, cannot guarantee to obtain an optimal assembly result with a little of assembly time and asmall damage risk on original segments. This is similar to the assembly practice in the machine assembly, where it is usually knowledge-intensive and decision making tools, e.g. CAM tools, are required. To reduce the reassembly time and risk, identifyingan optimal reassembly sequence and investigating thereassembly operation are needed. In reassembly, only referring a virtual or physical 3D prototype model is not sufficient for the reassembly process. Operators need decision making tools to analyze the reassembly problem, context and constraints, optimize the reassembly process and obtain reassembly knowledge, etc. However, currently, there is no systematic method or tool for aiding the reassembly process in the market or literature. Therefore, to fill this gap, this paper introduces an integrated method that uses both virtual and physical prototyping. A pilot experimental comparison case study is presented in the endfor method demonstration.

The remainders of the paper are organized as follows: Section 2 gives a literature review about related works; Section 3 introduces the proposed global integrated method; Section 4 develops an algorithm for reassembly sequence optimization; Section 5 presents a pilot experimental study with discussionsand the last section concludes with some perspectives on future work.

II. RELATED WORKS

Reassembly of 3D segmented object is an open and complex problem, which remains a scientific process of extreme interest for the archaeological community[1]. Usually, the solutions suggested by various research groups and universities depend on various aspects, such as the matching process of the broken surfaces, the outline of sherds or their colors and geometric characteristics, their axis of symmetry, the corners of their contour, the theme portrayed on the surface, etc.A comprehensive review work on matching and reconstructing three-dimensional of historical pottery fragments was conducted [2]. Although lots of research has been carried out for virtual reassembly, most of them focused on semi–automatic reassembly of the 3D model of a segmented object. The traditional physical reassembly process is usually conducted manually with a 3D full CAD model of the object as a reference. Very little work done is related with physical reassembly, e.g. sequence generation,reassembly operation.

Tableau1summarizes the current representative methods in the virtual reassembly of broken 3D objects.



No.	Articles	Authors	3D virtual Reassembly	Assembly sequence	Support structures
1	**Automatic Reconstruction of Archaeological Finds – A Graphics Approach**	Georgios P., Evaggelia-Aggeliki K. & Theoharis T. (2000)	Automatic ✗ Semi-Automatic ✓	✗	✗
2	**3D digital reassembling of archaeological ceramic pottery fragments based on their thickness profile**	Michail I. & Christos Nikolaos A. S (2016)	Automatic ✗ Semi- Automatic ✓	✗	✗
3	**Virtual Recovery of Excavated Relics**	Jiang Yu Zheng & Zhong Li Zhang (1999)	Automatic ✗ Semi-Automatic ✓	✗	✗
4	**Reassembling 3d thin fragments of unknown geometry in cultural heritage**	S.Y. Zheng, R.Y. Huang, J. Li & Z. Wang (2014)	Automatic ✗ Semi- Automatic ✓	✗	✗
5	**Virtual Vessel Reconstruction from a Fragment's Profile**	M. Kampel & F. J. Melero (2003)	Automatic ✗ Semi- Automatic ✓	✗	✗
6	**Assembling Virtual Pots from 3D Measurements of their Fragments**	Cooper et al,, (2001)	Automatic ✗ Semi-Automatic ✓	✗	✗
7	**Virtual assembly of pottery fragments using moire surface profile measurements**	Marie, I., & Qasrawi, H. (2005)	Automatic ✗ Semi-Automatic ✓	✗	✗
8	**On the automatic assemblage of arbitrary broken solid artefacts**	Papaioannou, G., & Karabassi, E. A. (2003).	Automatic ✗ Semi-Automatic ✓	✗	✗
9	**Automatic generation of ancient pottery profiles using cad software**	Badiu, I., Buna, Z., & Comes, R. (2015)	Automatic ✗ Semi-Automatic ✓	✗	✗
10	**3D Models for Cultural Heritage: Beyond Plain Visualization**	Scopigno, R. et al. (2011)	Automatic ✗ Semi-Automatic ✓	✗	✓
11	**Reassembling Fractured Objects by Geometric Matching**	Qi-Xing Huang et al. (2006)	Automatic ✗ Semi-Automatic ✓	✗	✗

Tableau 1. REPRESENTATIVE WORKS ON VIRTUAL REASSEMBLY OF BROKEN FRAGMENTS ([1, 3, 6-13])

Currently, the reassembly operation is still manually conducted in a trial and error manner. These methods are facing a couple of difficulties: large amount of time spent by the operator without sufficient reference and assembly sequence instruction; less customized tools, fixtures or temporary support structures; no precaution taken for joining fragile fragments andno reassembly training for operators. To solve these problems, this paper introduces an integrated method which is detailed in the next section.

III. INTEGRATED METHOD

The proposed integrated method uses both virtual and physical prototyping methods with allied tools. It has three main steps and they are described in Figure 1.

A. *Step 1: Prototyping*

The first step of the proposed method is prototyping, including both virtual and physical prototyping. There is a need to make an assumption that the segments of a target object are already identified and classified. This step will start after cleaning all the originalphysical segments of a segmented object. At first, digitization tools will be used to obtain the cloud points of segments and further get the CAD model of each segment. Then, traditional methods as discussed in the review section can be used to do the virtual reconstruction to get a full CAD model of the original broken object. In parallel, two other activities, physical prototyping and sequencing segments, to identify an optimal physical assembly sequence, are conducted. For physical prototyping, there exists a difference as compared to former methods. Here, not only a full physical model is printed through a 3D printing machine but also each individual segmentis printed. The printed segment prototypes and the identified optimal physical assembly sequence will be used for virtual model and assembly sequence validation as well as training practice in the next main step. To identify an optimal physical assembly sequence, the assembly constraints, objectives and other related information, e.g. operator preference, should be identified and structured. In the first step, the virtual and physical prototyping process can provide rich information on identifying assembly constraints and objectives. Generally, the outputs of the first step of this method include a full virtual model, physical prototypes of segments and the full model and a set of finite recommended alternative physical assembly sequences. Here, the physical assembly sequence is added as an additional reassembly reference, assembly instruction, to guide assembly operation.

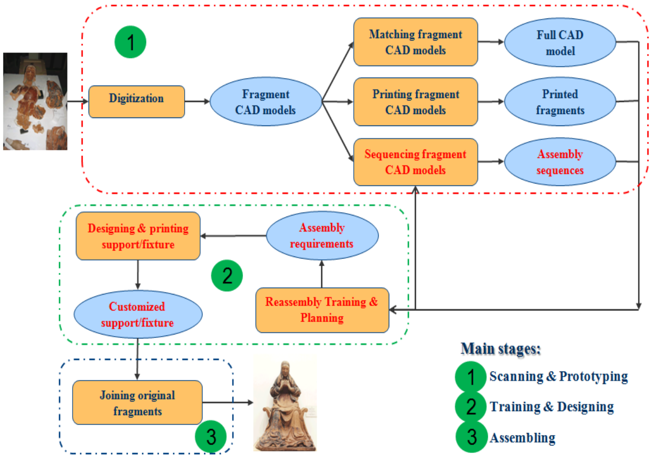


Figure 1. THREE STAGES FOR THE INTEGRATED REASSEMBLY METHOD

B. *Step 2: Training & Designing*

The second main step is assembly training and assembly tools or fixtures/support structures designing. As discussed above, without physical assembly practice, direct manual assembly with a virtual model as assembly references would be time consuming and damage the original segments with a higher risk, especially when the assembly operator is not experienced. Hence, as proposed in this method, a training activity is proposed. After prototyping and sequencing in the first step, physical prototypes and assembly instructions are generated. Operators can use recommended alternative assembly sequences to assemble the prototyped segment models so as to gain experience and get familiar to the physical assembly process. This step has three functions: a), to verify the virtual model and the recommended assembly sequences. If required, these models and assembly sequences can be modified. Additional assembly requirements could also be extracted from the assembly training to help identify better assembly sequences; b), to identify the need and specifications for designing customized fixtures, tools or support structures for the physical assembly process; c), to extract and reuse expert domain knowledge. In the assembly training and planning step, by applying a suitable method, experienced operator's assembly requirements, suggestions and skills could be recorded and structured. These can be reused as additional assembly requirementsto help identifying the better assembly sequence or as teaching instructions for green hand operators. If the assembly operators are familiar with the segments and assembly procedure after the training and have customized assembly tools and fixturesin this step, as expected, they should get better assembly quality with reduced time and damage risk.

C. *Step 3: Assembling*

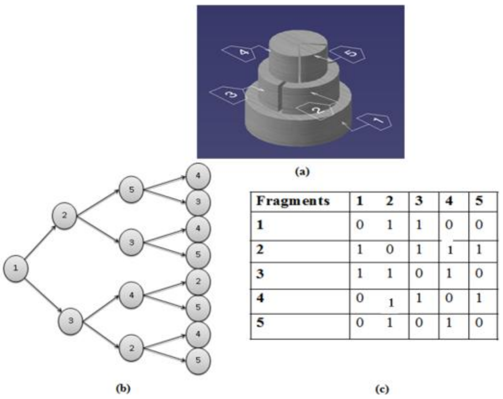
The final step is the physical assembly step, which will reconstruct the original broken object by using its segments. Currently, this job is mainly conducted manually with some common tools. However, customized fixtures, support structures and guide tools are not well developed. And there is no method or tool for aiding the development of these for the physical assembly process. In this proposed method, these supporting fixtures, structures and tools are considered and a design method will be developed to meet the practical needs as stated in[3].

Since the full method is still under implementation, the following sections of this paper only present some of the implemented work, assembly sequence optimization with a comparison experiment.

IV. ASSEMBLY SEQUENCE OPTIMIZATION

Assembly planning aims to identify and evaluate the different ways to construct a mechanical object from its components [4]. There are two methods for assembly sequence planning, direct method and indirect method. In direct method, assembly sequences for products are planned by simulating product assembly process [5]. However, in indirect method, disassembly sequence is planned first and then the disassembly sequence is reversed. The drawback of the direct method is that it is difficult to determine whether a previously assembled component can impede subsequent components to be assembled, and it usually takes many experiments to find a feasible assembly sequence. On the other hand, every successful disassembly operation corresponds to an assembly sequence. Similarly, the scientific core is the same in the assembly sequence planning for the reassembly of fragmented objects. In this research, the direct method for assembly sequence generation is adopted. The problem can be formulated as follows: given a geometrical and a content description of a fragmented 3D object, find an assembly sequence that satisfies the geometrical constraints and meets certain preset optimization criteria.

To identify the optimal assembly sequence, there are two sub tasks: generating alternative assembly sequences and evaluating these alternatives according to certain criteria. Theoretically, without considering any assembly constraint, a segmented 3D object with N pieces of fragments would have a solution space of $N!$, also called design space. However, there are usually some invalid or duplicate assembly sequences in the original solution space. To generate valid alternative assembly sequences without duplicates, this research applies clustering method and geometric constraints to filter those invalid ones. At first, an object's segments' interrelationships are clarified by using the virtual assembled CAD model of the object. The virtual assembled full CAD model is obtained by using traditional methods, as listed in Tableau 1, with human interaction. Then, a base segment, which is used as the assembly starting point, is identified using the rules: maximum mass and lowest gravity center along the object's original standing direction. After that, the 'dummy' segments, which will not affect the valid solution space since they only has one connection to other segment and can be regarded as a set of their connected segments, are removed.At last, geometric region constraint is used to divide all the fragments, except 'dummy' segments, into a set of adjacent assembly regions.



Fragments	1	2	3	4	5
1	0	1	1	0	0
2	1	0	1	1	1
3	1	1	0	1	0
4	0	1	1	0	1
5	0	1	0	1	0

Figure 2. (A). ASSEMBLED SEGMENTED OBJECT, (B). PRECEDENCE DIAGRAM AND (C). LIAISON MATRIX.

Figure 2 gives an example to show the alternative assembly sequences, represented by using precedence diagram, and the interrelations among segments, represented by a liaison matrix where '1' means there is a connection. From the liaison matrix, the 'dummy' segment can be identified. In a liaison matrix, each row or each column stands for the relationships between a segment and all the left segments. If the sum of each row or column is less than 2, which means the segment only has one connection to other segment. Then, this segment is a 'dummy' segment. Figure 3 shows an example with 'dummy' segments.

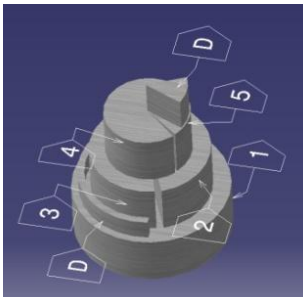


Figure 3. 'DUMMY' SEGMENT, MARKED BY 'D'

With the liaison matrix, segments can be clustered into a set of adjacent assembly regions. The first assembly region is the base segment, and then all the directly connected segments with the first region can be clustered as the second region, and so on. Figure 4 gives an example of a clustering result.

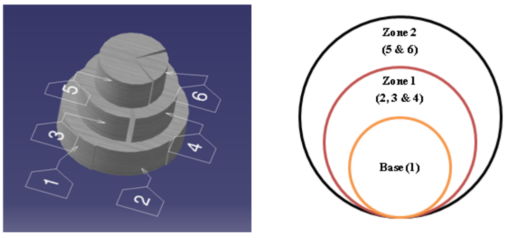


Figure 4. CLUSTERED FRAGMENTS IN ASSEMBLY REGIONS

In this research, another assumption is made that the final physical assembly of the original fragments is conducted according to the assembly regions in a sequential way, one by one, from the base segment to the furthest region. Therefore, when assembling thin wall hull objects, other geometric constraints, e.g. accessibility, are excluded and not considered here. As a result, the assembly sequence optimization problem is similar to the traditional TSP (traveler sales man problem) where each region should be visitedonly once but with alternative choices. Hence, a feasible solution space can be represented as:

$$\underline{\text{éq. (1) :}}\quad \Omega' = 1 \times (\mathrm{N}_{z2})! \times (\mathrm{N}_{z3})! \times (\mathrm{N}_{z4})! \cdots \times (\mathrm{N}_{zn})!$$

, where Ω' is the feasible solution space; $(N_{z1})!$ is the subset assembly sequence solution space of the ***i***th, ***i***=1, 2, …***n***, assembly region.

The next step is to evaluate the reassembly alternative sequences. In real practice, specific evaluation criteria can be set according to various requirements. Here, in this paper, with a demonstration objective, assembly stability criterion is defined and used as an evaluation criterion.An assembly sequence is said to be stable if it is progressed in such a way that the moving center of gravity or center of mass of the precedent assembled fragments falls within the line between the mass center of the base fragment and the mass center of the final assembly object. To have good stability during the reassembly process, the masscenter should be progressed in such a way that it's center of mass falling as much as close to the line between the masscenter of final assembled object and the mass center of the base fragment. Consider *R* and *B* representingthe masscenter of the assembled object and themass center of the base fragment respectively. Now, in an assembly step, if amasscenter, *D1*points in green color, of the precedent assembled fragments is very close to line RB, then it is more stable as compared to others, *D2* point in red color, shown in Figure 5. Therefore, the sum of the distances of moving mass centers to the line RB is used as an index to measure the stability.

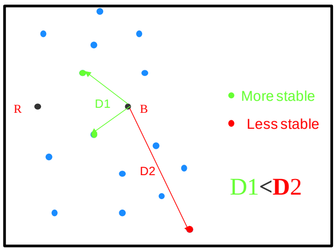


Figure 5. ASSEMBLY STABILITY DEFINITION

With this defined criterion, alternative assembly sequences can be valued by using accumulative distance of the moving mass centers to the line between the masscenter of final assembled object and that of the base fragment. Figure 6 shows the accumulative distances of three alternative assembly sequences. For example, the accumulative distance of sequence colored in green in Figure 6 is the sum of *d(1-2)* and *d(1-2-3).*

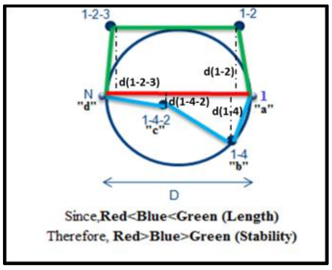


Figure 6. ACCUMULATIVE DEVIATION DISTANCE

For demonstration objective, a simple algorithm, as shown by Figure 7, is developed to solve the evaluation task.

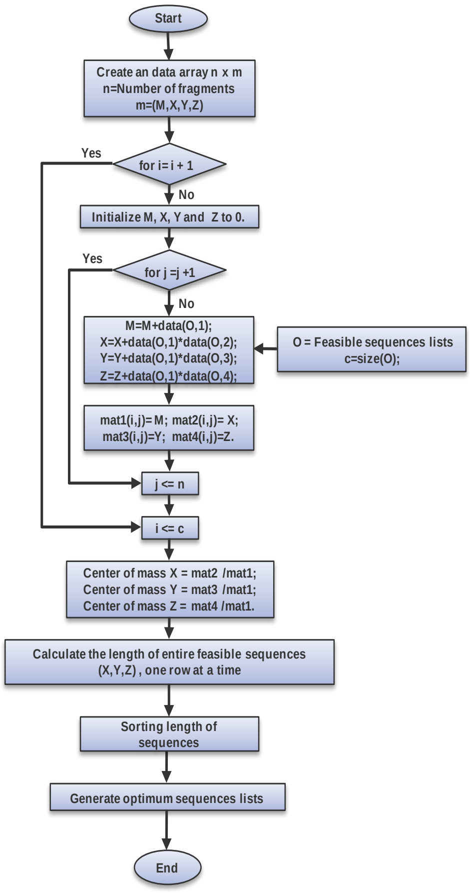


Figure 7. ALGORITHM FOR GENERATING OPTIMUM STABILITY ASSEMBLY SEQUENCES LIST

V. COMPARISON EXAMPLE

To show the potentials of the proposed integrated method, a comparison study is presented in this section. A fragmented cup is assembled by two groups of students with the current practice and the proposed method, partially implemented, respectively. The broken cup and its virtual model are shown in Figure 8 below.To simplicity the assembly process, only 10 segments of the broken cup are used in the experiment. Each segment of the cup was digitized and refined in the Geomagic software environment (*http://www.geomagic.com/fr/*). Virtual reassembly was conducted manually since the example is relatively simple. In real practice, when facing complex models, current methods in literature as presented in Table 1 above can be adopted.

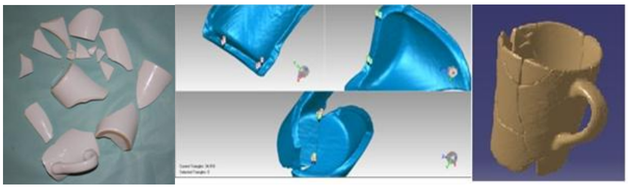


Figure 8. FRAGMENTED OBJECT AND ITS VIRTUAL RECONSTRUCTION

Then, the next step is to select the base segment and classify all the left segments into assembly regions. Here, the mass of segment is used a criterion for identifying the base segment. The segment that is the heaviest is selected. In real practice, different criteria can be defined for identifying an optimal base segment.After computing by applying the developed algorithm, a set of alternatives are generated and recommended for next steps, e.g. assembly training, according to their ranking as shown in Figure 9.

$$K$$

$$\begin{bmatrix}
1 & 2 & 3 & 7 & 5 & 6 & 10 & 8 & 4 & 9 \\
1 & 2 & 3 & 7 & 5 & 6 & 10 & 4 & 8 & 9 \\
1 & 2 & 3 & 7 & 5 & 6 & 10 & 8 & 9 & 4 \\
1 & 2 & 7 & 3 & 5 & 6 & 10 & 8 & 4 & 9 \\
1 & 2 & 7 & 3 & 5 & 6 & 10 & 4 & 8 & 9 \\
1 & 2 & 7 & 3 & 5 & 6 & 10 & 8 & 9 & 4 \\
1 & 2 & 3 & 7 & 5 & 6 & 8 & 10 & 4 & 9 \\
1 & 2 & 3 & 7 & 5 & 6 & 10 & 4 & 9 & 8 \\
1 & 2 & 3 & 7 & 5 & 6 & 10 & 9 & 8 & 4 \\
1 & 2 & 3 & 7 & 5 & 6 & 8 & 10 & 9 & 4 \\
1 & 2 & 3 & 7 & 5 & 6 & 10 & 9 & 4 & 8 \\
1 & 2 & 7 & 3 & 5 & 6 & 8 & 10 & 4 & 9 \\
1 & 2 & 7 & 3 & 5 & 6 & 10 & 4 & 9 & 8 \\
1 & 2 & 3 & 7 & 5 & 6 & 4 & 10 & 8 & 9 \\
1 & 2 & 7 & 3 & 5 & 6 & 10 & 9 & 8 & 4 \\
1 & 2 & 7 & 3 & 5 & 6 & 8 & 10 & 9 & 4 \\
1 & 2 & 7 & 3 & 5 & 6 & 10 & 9 & 4 & 8 \\
1 & 2 & 7 & 3 & 5 & 6 & 4 & 10 & 8 & 9 \\
1 & 2 & 3 & 7 & 5 & 6 & 8 & 4 & 10 & 9 \\
1 & 2 & 3 & 7 & 5 & 6 & 4 & 8 & 10 & 9
\end{bmatrix}$$

Figure 9. OBTAINED ALTERNATIVE ASSEMBLY SEQUENCES

After that, the segments are printed by using an FDM (fused modeling deposition) machine. These printed segments with the obtained alternative assembly sequences are used to train a group of students. While for the other group in comparison, only the full virtual model is provided for them to get familiar with the object in the training time of the training group. Here, the training time is set as 10 minutes, and no further instruction is provided except the optimal assembly sequence, the first row in Figure 9. Students use the obtained assembly sequence to assemble the printed plastic segments as shown in Figure 10.

Figure 10. ASSEMBLY TRAINING WITH PRINTED PLASTIC SEGMENTS

Finally,each student in the two groups isasked to join the original broken cup with binder one by one to measure the assembly time. The cup was joined and decomposed in turns for student's experiment. This can make sure that they were assembling the same object. The assembly conditions for the two different groups are presented in Figure 11 and the assembly comparison results are presented in Table 2. It shows that the group with assembly sequence and assembly training saves assembly time.

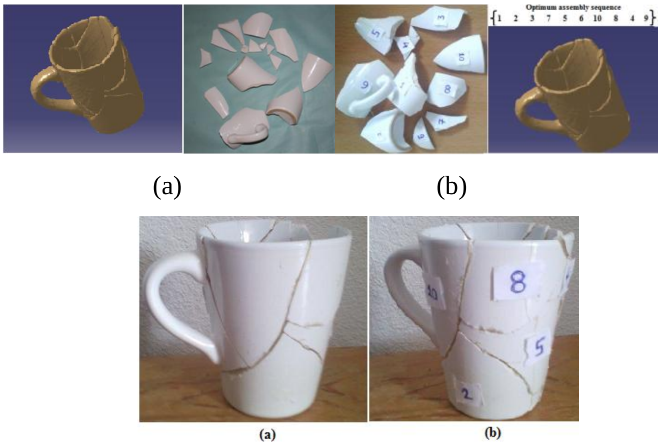


Figure 11. ASSEMBLY CONDITIONS AND RESULTS

Participant	***Optimum assembly sequence***	***Assembly training***	***Average Time consumed (min)***
Group (a)	✗	✗	6.5
Group (b)	✓	✓	3.4

Tableau 2. ASSEMBLY COMPARISON RESULT

As shown by the experiment result, the assembly sequence and physical assembly training can help operators reducing the assembly time. Due to the simplicity of the object, other advantages are not so obvious, even the time gained is not so remarkable. Since both of the two groups have good knowledge about the shape of a cup. However, as discussed before, when facing complex segmented objects with unfamiliar or even unknown shapes and large quantity of fragments, the advantages brought by training with recommended assembly sequence would appear and be expected to make a big difference. In addition, the assembly training can avoid the touching of original segments as did by the operators in Group (a) to cause further damage when facing fragile segments. This is also valuable in several application contexts, e.g. surgical planning and relics repairing.In general, the presented experimental study is mainly used for method demonstration. For real application context, more works should be done to improve and adapt the proposed sequence optimization method to meet specific application requirements.

A. *Assembly base segment identification*

The assembly base segment determines the starting point of assembly and the assembly region classification. This would imply the solution space and the further used assembly supporting structures, fixtures and tools. Hence, specific attention should be paid to develop a method or a decision making tool for helping identify base segment for specific application context regarding the assembly constraints and objectives in different environments.

B. Assembly constraints and objective determination

As discussed before, traditionally, there are various assembly constraints and objectives. Before evaluating the alternative assembly sequences, the main concerned assembly constraints and objectives should be identified according to application requirements. They can be used to define the solution space and construct fitness function for optimization algorithm. However, this is not an easy issue for some application domains, e.g. surgical planning, and hence domain knowledge is usually required for this task.

C. Optimization algorithm development

In this example, the performance of the algorithm is not discussed since the object is not complex and the number of segments is small. However, for real applications, the algorithm should be improved to guarantee a good computation performance when facing large scale number of segments and multi-objective optimization, where more advanced heuristic searching methods, e.g. evolutionary algorithms, should be applied.

VI. CONCLUSION AND FUTURE WORKS

This paper proposes an integrated method for supporting the physical assembly process for segmented objects. Both virtual and physical prototyping methods and tools are used. Assembly sequence optimization and physical assembly training are defined and proposed for the physical reassembly. A comparison experimental study shows the potentials of assembly sequence optimization and physical training. In future,advanced physical training method and related setup, e.g. augmented reality and haptic tools, will be developed for aiding assembly training. In addition, design method and tools based on 3D printing will be developed to help design and manufacture customized low cost support structures, fixtures and tools for aiding the physical reassembly process. Finally, an interactive assembly support platform that applies the proposed method in this paper is expected to be developed.

REFERENCES

[1] Stamatopoulos, Michail I., and Christos-Nikolaos Anagnostopoulos. "3D digital reassembling of archaeological ceramic pottery fragments based on their thickness profile." arXiv preprint arXiv:1601.05824 (2016).

[2] Rasheed, Nada A., and Md Jan Nordin. "A Survey of Computer Methods in Reconstruction of 3D Archaeological Pottery Objects." International Journal 3.3 (2015): 712-714.

[3] Scopigno, Roberto, et al. "3D Models for Cultural Heritage: Beyond Plain Visualization." Computer 44.7 (2011): 48-55.

[4] Dong, Tianyang, et al. "A knowledge-based approach to assembly sequence planning." The International Journal of Advanced Manufacturing Technology 32.11-12 (2007): 1232-1244.

[5] Jiang, Hua, et al. "Assembly sequence planning for mechanical products." Tsinghua Science and Technology 4.2 (1999): 1436-1439.

[6] Papaioannou, Georgios, Evaggelia-Aggeliki Karabassi, and Theoharis Theoharis. "Automatic Reconstruction of Archaeological Finds–A Graphics Approach." International Conference on Computer Graphics and Artificial Intelligence (3IA 2000 Proceedings). 2000.

[7] Zheng, Jiang Yu, and Zhong Li Zhang. "Virtual recovery of excavated relics." IEEE Computer Graphics and Applications 19.3 (1999): 6-11.

[8] Zheng, S. Y., et al. "Reassembling 3D Thin Fragments of Unknown Geometry in Cultural Heritage." ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences 2.5 (2014): 393.

[9] Kampel, Martin, and Francisco J. Melero. "Virtual vessel reconstruction from a fragment"s profile." Proceedings of the 4th International conference on Virtual Reality, Archaeology and Intelligent Cultural Heritage. Eurographics Association, 2003.

[10] Cooper, David B., et al. "Assembling virtual pots from 3D measurements of their fragments." Proceedings of the 2001 conference on Virtual reality, archeology, and cultural heritage. ACM, 2001.

[11] Papaioannou, Georgios, and Evaggelia-Aggeliki Karabassi. "On the automatic assemblage of arbitrary broken solid artefacts." Image and Vision Computing 21.5 (2003): 401-412.

[12] Badiu, Ionut, Zsolt Buna, and Radu Comes. "Automatic Generation of Ancient Pottery Profiles Using CAD Software." Jounral of Ancient History and Aechaeology. 2.2 (2015).

[13] Huang, Qi-Xing, et al. "Reassembling fractured objects by geometric matching." ACM Transactions on Graphics (TOG). Vol. 25. No. 3. ACM, 2006.