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The Thickness Profile method: A new digital 3D approach for reassembling unpainted archaeological ceramic pottery

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Abstract – The reassembly of a broken archaeological ceramic pottery from its fragments (called sherds) is an open and complex problem, which remains a scientific process of extreme interest for the archaeological community. All the solutions suggested by various research groups and universities, depend on external information such, the outline of sherds, the corners of their contour, some geometric characteristics, the matching of the discontinued surfaces due to fracture, the angles and curves on its boundaries, etc. In our approach the reassembly process is based on a different and more secure idea, since it is focuses on the thickness information encapsulated in the inner part of the sherds, which is not -or at least not heavily- affected by the presence of harsh environmental conditions and is safely kept within the sherd itself. The method is verified in various use case experiments, using cutting edge technologies and precise measurements on 3D models.

I. INTRODUCTION

In every archaeological excavation, a variety of small ceramic pottery fragments (called sherds or ostraca) are revealed, which will provide valuable data for the excavation. The nature of these objects (due to four elements, soil, water, heat and air) give them some special properties and make them highly resistant to time and wear. Moreover, sherds are not stolen, they remain to the place where the pottery is destroyed and like little papyri, they carry unique undeleted information over the centuries. The quantity and the high value of such information, rightly gives to sherds, the title of best data carrier from ancient times to our days. For the reassembly of a ceramic pottery, the majority of the scientific methods suggested by various research groups, depend on external information such, the outline of sherds, the corners of their contour, some geometric characteristics, the matching of the broken surfaces, the angles and curves on its boundaries the axis of symmetry, the colors, or even the theme portrayed on it [1-10], [12].

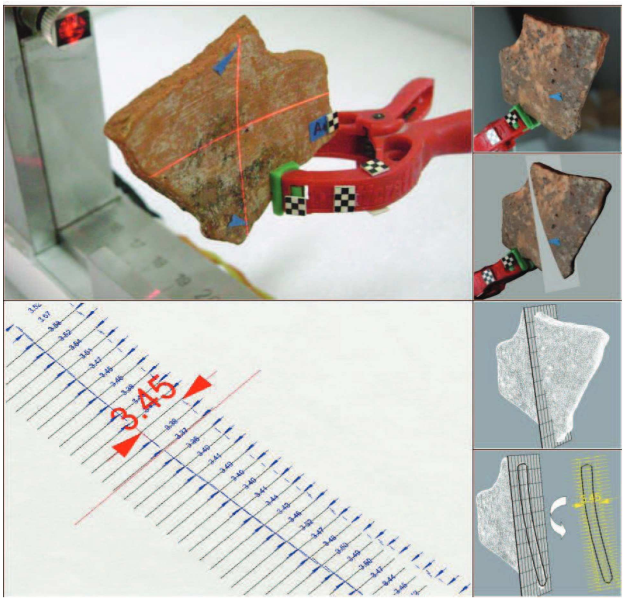

Fig. I. The Thickness Profile method.

All these techniques suffer from the problems introduced by the external wear and decay of the material during the exposure in the soil [13]. As a result, many characteristics on the surface of the sherds have been altered during the long time of exposure, leading to severe decrease in the efficiency of research methods based on external characteristics.

II. THE THICKNESS PROFILE METHOD

The proposed methodology is based on a new approach that can be considered scientifically more effective than others, as we seek important information encapsulated inside the core of the sherd and not on its surface. Our approach works even if some of the sherds are missing, it is not affected by the presence of external wear and damages, nor by the geometrical shapes or by the colour degradation of the pottery. The new method is based on exploration, extraction and utilization of all possible

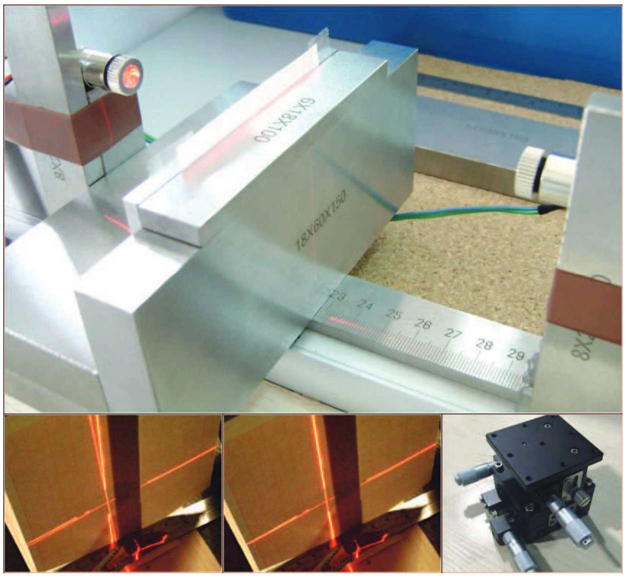

Fig. II. Our specialized equipment.

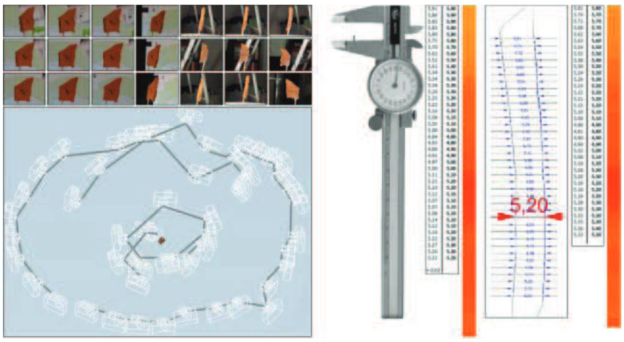

Fig. III. The photogrammetric process and the accuracy achieved.

thickness information (i.e. Thickness Profile) which may have encapsulated inside each sherd. All this information, as a sequence of numbers, can be sorted, compared and provide a complete and efficient solution for the complex problem of reassembling of a broken pottery. The basic idea is based on the fact that as the potter artist rotates the pliable clay on the wheel to create the pottery, he/she creates distinguishing thickness measurements, which are unaltered and they can easily be detected. The gradual construction of a pottery on a wheel, starts from the base, continues up to the main body and usually ends at the neck and at the rim. This gradual upward movement of the artist in the clay body, creates a certain thickness profile which can be detected, as they vary, with absolute certainty, from point to point, from height to height and of course from pottery to pottery. This distinction generates the image of a structure, which resembles a stack of horizontal rings, with specific thickness in relation to the pottery height. Specifically, as the fingers of potter push outwards (expansion of the clay body), the clay in these points is getting thinner, while in the case of inward pressure (contraction of the clay body) the clay is getting thicker. Based on the above, it is reasonable to consider, that each sherd can theoretically fit to a specific point of the stack of rings and hence to a corresponding point in the overall thickness profile or thickness contour of a particular pottery. The new proposed methodology comprises of three basic steps, namely: i) the appropriate orientation (Fig.I) and 3D scanning (Fig.III/left) of each fragment, ii) the extraction of their optimal thickness profile as an intersection of the 3D model with a properly oriented vertical plane (Fig.IV/a) and iii) the repetitive process (Fig.IV/d) for maximizing matching results between TPs in order to achieve a locally optimal alignment between possibly neighboring sherds (Fig.IV/c).

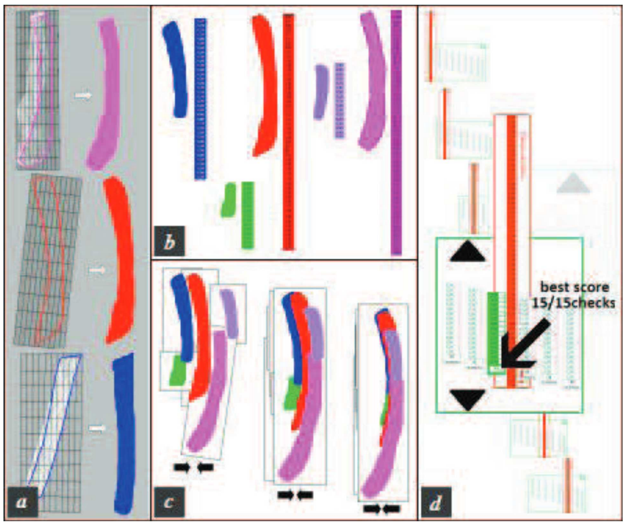

Fig. IV. The matching process.

A. Creation of 3D models

As it is absolutely necessary for the archaeologists, to obtain the appropriate profile measurements without damaging the sherds, our method is implemented and validated using their identical 3D models, making the extraction of measurements fully reproducible and non-intrusive for the sherd itself. Initially, on each sherd we choose and draw a specific vertical straight line (Fig.I) through which we expect to extract the largest possible thickness profile. For the process we use some special crosshair beam lasers and a special stable XYZ positioning platform (Fig.II). Then each sherd is placed on a stable basis and photographed panoramic, from close distance, from all sides and from various angles (Fig.III/top-left). The result is a set of 30 photos for each sherd, which is then transformed into a 3D model (point cloud/mesh), using a specialized photogrammetry software (Fig.III/bottom-left).

B. Thickness Profile extraction

It is very important to detect the ideal vertical plane in every sherd that carries the richest thickness information.

The highest vertical plane to the horizontal rings is selected that allows the extraction of the maximum possible thickness profile (Fig.IV/a). This is especially important, since the best possible thickness profile for each sherd is needed, in order to perform the optimum thickness matching result (best “score”) between neighboring sherds. This vertical flat plane is absolutely oriented with the horizontal inner lines of the sherd and using an appropriate 3D modelling software, the TP of the sherd is calculated accurately. For the calculation, we perform thickness sampling for every 1mm (Fig.I).

C. Thickness Profile matching

Following the previous steps, by the process of sliding small thickness profiles across larger ones (Fig.IV/b) until the achievement of optimum fit, the method retrieves candidate matches between sherds performing local score optimization (Fig.IV/d). The thickness profile method, is a semi-automatic method, as in the case of two adjoining sherds, it cannot decide which one will be placed left and which will be placed right. At this point the expert eye of the archaeologist-user, should give the correct arrangement (left or right). In addition, small sherds usually do not have the ability to give adequate thickness information and therefore the probability for erroneous arrangement is increased. For these reasons, the process is done in stages, starting from the largest available sherd and moving gradually to the smaller ones. Starting from a master sherd, the main target is to stack progressively more and more thickness information (Fig.IV/c) and thus greater thickness profile, increasing the chances to match the remaining sherds in the right place. Hence, at the beginning of the process, the largest available sherd is assigned with the role of the “driver” (master sherd) and as the process is executed and two or more pieces are matched together, a single meta-sherd is formed with an increased thickness profile (Fig.IV/c). Intuitively, this corresponds to virtually gluing sherds together, while the matched parts of TPs become common values to TP of the meta-sherd. This approach ensures that parts of TPs that have previously been matched in the some pair of sherds are no longer considered for future pairings. Our matching procedure looks like a “fluctuation” smaller thickness profiles on larger ones. The search for the ideal match, could be found only if two profiles fit perfectly together and the sequential numbers of the small sherd match somewhere in the sequence of numbers of the large sherd. Our method is based on the plurality of measurements and less in the high accuracy of measurements. Therefore, the method is searching for the best “score”, with the fewer differences in most possible comparisons. The best “score” is defined as the sum of the absolute differences between the more possible comparisons between two sherd profiles (Fig.IV/d).

III. A REAL POTTERY FROM 400 B.C.

In this section we demonstrate the thickness profile method on a real theme from the past (400 B.C.). Specifically we use nine small fragments (Fig.V/below), from an unpainted real ancient ceramic pottery, probably from a Lopas (Fig.V/above), which constitutes an unglazed cooking pottery (chytra).

Fig. V. Two complete Lopas are illustrated above [11]. Bellow the nine real small sherds.

The fragments is from an excavation, very close to a sea coast of Athens. Some sherds of the pottery has been damaged. Figure VI, demonstrates the various views of sherds, the acquired 3D models and the extraction of the optimal plane for the calculation of the distinctive thickness measurements.

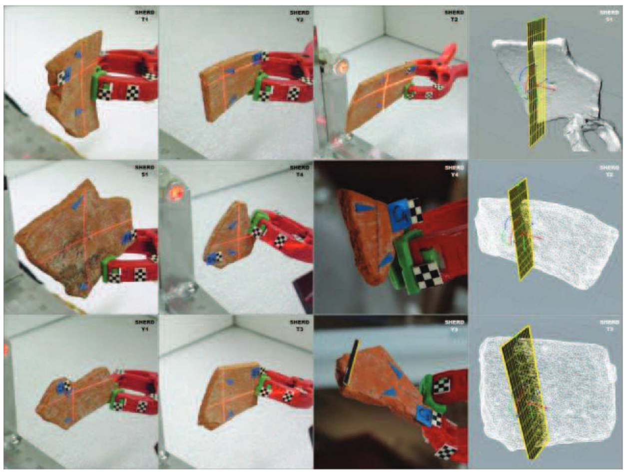

Fig. VI. Multiple views of sherds and the extraction of their optimal thickness profiles.

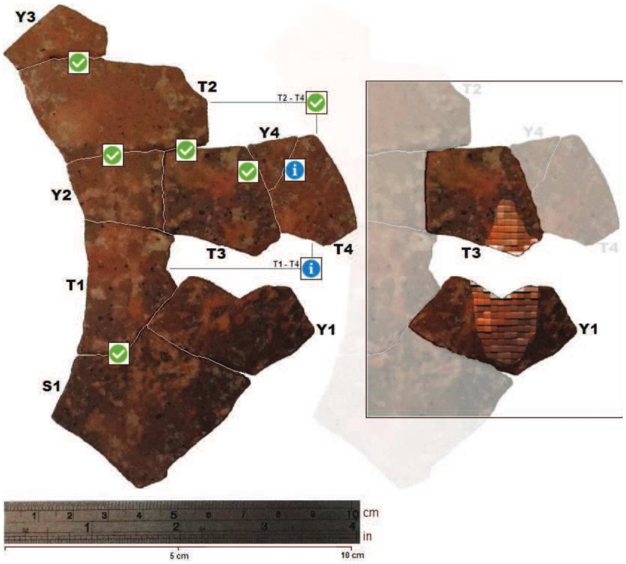

Fig. VII. The reassembled external surface of Lopas.

Table 2, indicates all the thickness measurements from the sherds in this example. Figure VII/left, presents the final reassembled external surface of the nine assembled fragments. The sherds with id T3 and Y1, have a local "swelling gap" as marked in Figure VII/right, and therefore cannot easily be matched with others. Even in this very difficult case with very small and some "damaged" fragments, our method achieved very satisfying results, as shown in Table 1.

Table 1. The results from the Lopas experiment.

pair	suggesting position					annotation	
(Y3) vs (T2) 15/ 25, 5	in out	38,00 5,00	15 CH 5 CH	+1mm (M) -10mm (oM)		R E J E C T FULL MATCH!	
(T1) vs (S1) 37/ 39, 15	in out	37,00 14,00	37 CH 26 CH	+1mm (R) -11mm (oM)		R E J E C T FULL MATCH !	
(T4) vs (T1) 25/ 37, 5	in out	33,00 3,00	25 CH 5 CH	+12mm (R) -20mm (oM)		R E J E C T POSSIBLE MATCH	
(T4) vs (T2) 25/ 25, 5	in out	64,00 6,00	25 CH 24 CH	+1mm (M) -16mm (Mu)		R E J E C T FULL MATCH !	
(Y4) vs (T4) 12/ 25, 5	in out	8,00 7,00	12 CH 11 CH	+1mm (M) -1mm (oM)		R E J E C T POSSIBLE MATCH	
(Y4) vs (T3) 12/ 26, 5	in out	10,00 4,00	12 CH 9 CH	+1mm (M) -3mm (oM)		R E J E C T FULL MATCH !	
(T3) vs (T2) 26/ 25, 5	in out	0,00 4,00	26 CH 25 CH	+0mm ( ) -18mm (Mu)		- FULL MATCH !	
(Y2) vs (T2) 19/ 25, 5	in out	38,00 5,00	19 CH 18 CH	+7mm (M) -21mm (Mu)		R E J E C T FULL MATCH !	

The results validate that our method allows for accurate reassembly of the nine sherds to be achieved with minimal human interaction. Our software defines the point of matching and the human interaction involves the correct placement of the fragments to the left of to the right of the "master" sherd. It should be noticed, that the thickness profile method is effective even if some (or many) small pieces of the pottery are still missing. This has significant implications for archeology since until now, manual reassembly is usually based on contour-based methods that exploits local surface characteristics on the fragments.

However, if such small parts are missing or are altered, severe problems in the reassembly process are imposed.

IV. ACCURACY COMPARISON

A critical point for the success of thickness profile method is the thickness precision that the researcher can retrieve from the available sherds. To our knowledge, the average thickness size of sherds, usually lies between 2-15mm. These limits are fully confirmed on all the exposed sherds in the National Archaeological Museum in Athens. Our methodology requires discrimination capabilities in hundredths of a millimeter (0.01mm). In order to demonstrate the accuracy, we used a caliper (Helios dial caliper) to manually capture the thickness measurements from a specific sherd. The measurements were then compared against those acquired using photogrammetry and 3D software. Figure III/right, present the results, depicting on the left column the measurements using the caliper and on the right those acquired by photogrammetry. On both ends, left and right respectively, the respective color map is illustrated (completely distinct and nearly identical).

Table 2. The acquired TPs from Lopas sherds.

S1	T1	T2	T3	T4	Y1	Y2	Y3	Y4
3,52	3,57	2,82	3,13	2,98	4,16	3,40	2,70	3,23
3,57	3,62	2,88	3,17	3,08	4,13	3,45	2,68	3,27
3,58	3,64	2,93	3,20	3,13	4,10	3,50	2,73	3,20
3,52	3,63	2,94	3,24	3,17	4,11	3,41	2,76	3,22
3,54	3,64	2,96	3,30	3,21	4,07	3,42	2,77	3,28
3,51	3,67	2,99	3,38	3,27	4,08	3,40	2,75	3,28
3,47	3,68	3,02	3,40	3,31	4,09	3,37	2,75	3,30
3,45	3,69	3,08	3,42	3,36	4,10	3,38	2,75	3,34
3,45	3,66	3,04	3,48	3,40	4,12	3,37	2,75	3,38
3,38	3,68	3,07	3,54	3,43	4,12	3,38	2,78	3,40
3,43	3,67	3,13	3,55	3,48	4,13	3,37	2,78	3,39
3,43	3,63	3,13	3,59	3,47	4,16	3,38	2,77	3,45
3,44	3,61	3,15	3,61	3,43	4,16	3,37	2,78	
3,38	3,62	3,16	3,66	3,41	4,10	3,36	2,78	
3,37	3,61	3,17	3,70	3,39	4,07	3,34	2,76	
3,36	3,56	3,16	3,76	3,45		3,34		
3,40	3,54	3,20	3,78	3,47		3,38		
3,41	3,50	3,21	3,81	3,46		3,39		
3,40	3,47	3,23	3,81	3,49		3,41		
3,40	3,46	3,28	3,84	3,44				
3,40	3,44	3,30	3,86	3,48				
3,41	3,43	3,31	3,89	3,49				
3,44	3,44	3,31	3,94	3,52				
3,43	3,42	3,36	3,98	3,55				
3,46	3,44	3,38	4,01	3,57				
3,52	3,45		4,14					
3,47	3,43							
3,48	3,46							
3,50	3,48							
3,49	3,50							
3,50	3,50							
3,47	3,50							
3,44	3,54							
3,45	3,56							
3,42	3,54							
3,43	3,55							
3,42	3,54							
3,40								
3,38								

V. VALIDATION ON SYNTHETIC DATA

Using exact hand-made replicas of ceramic potteries, we demonstrate in this section the accuracy and efficiency of the proposed method. A replica is intentionally broken (Fig.X) and the pieces are digitally reassembled successfully by the TP method. Before breaking them, horizontal and vertical lines were marked on the surface

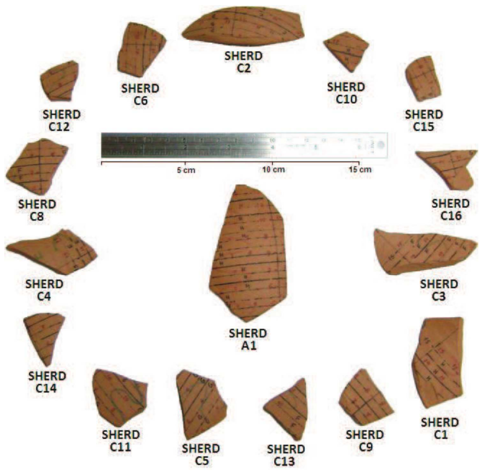

Fig. VIII. The 15 small sherds "Dwarfs" against the "Giant".

to confirm our methodology. Specifically, the pottery was placed on a horizontal surface and concentric circular contours (every 0.5cm) were drawn in its external surface. Furthermore the outer surface is partitioned into eight different vertical areas (i.e. A, B, C, D, E, F, G and H) using vertical lines at 45, 90, 135, 180, 225, 270, 315 and 360 degrees (Fig.X/top-left).

A. The "Dwarfs and the Giant" experiment

During the reassembly of the replica the available material includes also small fragments which have little identification information and thus complicate the task of reconstruction. For this complex scenario, we have chosen to show in details the value of thickness profile method. With our special software based on TP, 15 very small sherds (Dwarfs) were placed successfully against

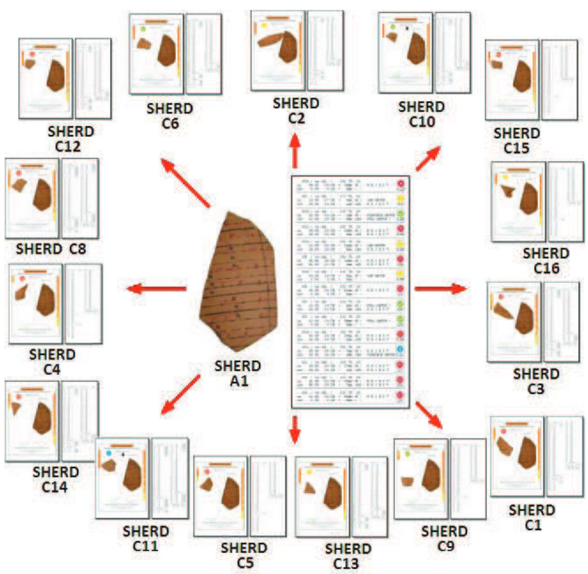

Fig. IX. The software results for each pair and the aggregated page.

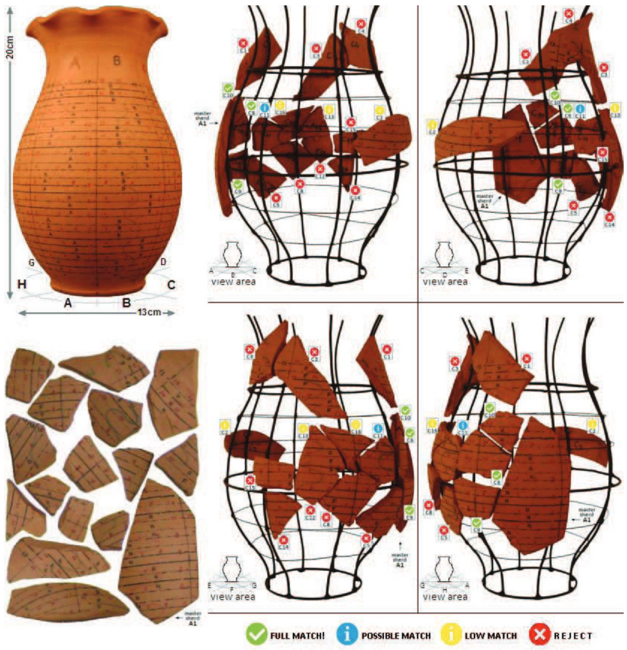

Fig. X. The "Dwarfs and the Giant" experiment.

the largest available sherd A1 (the Giant). For the "Dwarfs and the Giant" experiment, we used all the available thickness measurements that we had from the processes. For each pair of sherds, the software created a two pages report (Fig.IX), with all the necessary information for the guidance of the archaeologist (one of the two pages in full graphical).

Table 3. The results from "Dwarfs and the Giant".

pair	suggesting position				annotation
(C15) vs (A1)	in	35,00	15 CH	+30mm (M)	R E J E C T
15/ 70, 15	out	0,00	0 CH		
(C2) vs (A1)	in	19,00	17 CH	+6mm (M)	LOW MATCH
17/ 70, 15	out	20,00	16 CH	-1mm (oM)	R E J E C T
(C10) vs (A1)	in	20,00	19 CH	+1mm (R)	POSSIBLE MATCH
19/ 70, 15	out	12,00	15 CH	-4mm (oM)	FULL MATCH!
(C12) vs (A1)	in	38,00	20 CH	+13mm (M)	R E J E C T
20/ 70, 15	out	49,00	15 CH	-5mm (oM)	R E J E C T
(C13) vs (A1)	in	22,00	20 CH	+10mm (M)	LOW MATCH
20/ 70, 15	out	24,00	15 CH	-5mm (oM)	R E J E C T
(C8) vs (A1)	in	41,00	25 CH	+19mm (M)	R E J E C T
25/ 70, 15	out	42,00	21 CH	-4mm (oR)	R E J E C T
(C16) vs (A1)	in	16,00	14 CH	+5mm (M)	LOW MATCH
14/ 70, 15	out	0,00	0 CH		
(C5) vs (A1)	in	33,00	15 CH	+41mm (M)	R E J E C T
15/ 70, 15	out	0,00	0 CH		
(C6) vs (A1)	in	12,00	19 CH	+8mm (M)	FULL MATCH!
19/ 70, 15	out	33,00	16 CH	-3mm (oM)	R E J E C T
(C9) vs (A1)	in	12,00	13 CH	+38mm (M)	FULL MATCH!
13/ 70, 15	out	0,00	0 CH		
(C14) vs (A1)	in	52,00	20 CH	+37mm (M)	R E J E C T
20/ 70, 15	out	42,00	15 CH	-5mm (oR)	R E J E C T
(C11) vs (A1)	in	35,00	25 CH	+7mm (M)	R E J E C T
25/ 70, 15	out	15,00	16 CH	-9mm (oM)	POSSIBLE MATCH
(C1) vs (A1)	in	20,00	16 CH	+27mm (M)	R E J E C T
16/ 70, 15	out	54,00	15 CH	-1mm (oM)	R E J E C T
(C3) vs (A1)	in	41,00	22 CH	+25mm (R)	R E J E C T
22/ 70, 15	out	50,00	15 CH	-7mm (oM)	R E J E C T
(C4) vs (A1)	in	12,00	10 CH	+49mm (R)	R E J E C T
10/ 70, 15	out	0,00	0 CH		

At the end of the process, the software prints an aggregated page (Fig.IX/center) that includes information for all the sherds as shown in Table 3. It should be emphasized that in cases of small sherds that are not adjoined with the master sherd, the TP method successfully places them in the appropriate height based on the overall thickness profile or thickness contour of the pottery. For illustration purposes, all the 15+1 small sherds from the pottery (i.e. Dwarfs+Giant), were placed on a metal mesh for demonstrating the effectiveness of our method and the respective software (Fig.X/top-right).

VI. CONCLUSIONS

We presented a new digital approach for reassembling ancient ceramic pottery based on 3D models of their fragments and the exploitation of their thickness profile. The results show that our method allows for accurate reassemblies to be achieved with minimal expert interaction. The method is based on thickness, which is an information encapsulated in the inner part of the sherd that cannot be affected by the presence of harsh environmental conditions. Our method is verified on real and synthetic potteries. Using photogrammetry, 3D representations and precise measurements we demonstrated the validity of new method. To our knowledge, we have introduced a new method that bridges the gap between top-down and bottom-up approaches and answers difficult problems in the excessively time consuming task of manual reassembly of ancient pottery. We intend to expand and fine-tune our methodology with more complex experiments using real archaeological potteries from some museum collection in high archaeological interest countries (especially on themes from Archaic, Classical or Hellenistic period).

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