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A Survey of Computer Methods in Reconstruction of 3D Archaeological Pottery Objects

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Abstract

An automatic reconstruction of ancient artifact fragments is of great interest in archaeology, and is considered important because it helps archaeologists make inferences about past cultures and civilizations. Therefore, numerous researches proposed various methods to put together and restore the fragments of a piece of pottery to its original form. The aim of this paper is to present an in-depth review of the most important available publications in computer applications related to the area of the classifying and reconstruction of three-dimensional model for archaeological pottery objects over the epoch in the early eighties until the end of 2013. This task classified according to the feature extraction, the classification process and the matching techniques implemented for the purpose of restoration of the fragments of pottery object to its original form. Moreover, this paper focused on review and analyze the results that they have achieved.

INTRODUCTION

Archaeology is the scientific study of the last remnants of humanitarian civilization, which means exploring the lives of ancient peoples by examining their waste, and discovering human activity in the past through the recovery and analysis of the material culture and environmental data that they have left behind, which includes artifacts, architecture and cultural landscapes. Incidentally, it should be mentioned that the area of ceramics is one of the most common in archaeology in terms of ancient fragments (Kampel & Sablatnig 2004). Hence, the reconstruction of unknown objects from a large number of smaller pieces may involve thousands of irregular fragments, and is a tedious task, especially in case of the loss some pieces. It sometimes requires laborious effort, and may take years of tedious work and may involve a great number of laborers and experienced archaeologists. The laborers and archaeologists involved must deal with the artifacts cautiously to avoid further damage, especially with the edges of fragments, when they attempt to assemble the fragments manually, because assemble the fragments are similar to assemble the pieces of a jigsaw puzzle (Castañeda et al. 2011; Funkhouser et al. 2011). Numerous archaeologists challenged the task of achieving the accurate reassembly of the archaeological fragments and returning them to their original form because of the high value in information that represents past civilizations and cultures. This paper will carry out a review to the studies that were performed using computers to retrieval archaeological excavation fragments into their original form. The main objective of the review of previous studies is to facilitate the task of subsequent studies by proposing new algorithms in order to achieve better results than the previous algorithms.

This paper is structured into several sections. An overview of the reconstruction of fragmented objects is presented in Section 2, the structure search is drawn in Section 3, and Section 4 provides studies performed during the period eighties until the end of 2013. An important analysis is presented in Section 5. Finally, Section 6 summarizes and highlights the most important conclusions.

2- Reconstruction of Fragmented Objects

The world has witnessed great development in the performance of computers as the use of image processing and pattern recognition techniques, which encouraged researchers to attempt to solve the problem of reconstruction of

fractured objects from a large collection of randomly mixed fragments via proposed systems instead of manually assembling them, which is a tedious and time consuming task. To overcome this problem, several authors have worked on the automated reconstruction of fragmented objects, and the core concept of this problem is finding a solution for many applications. One application is reconstructing torn documents (Richter et al. 2011; Lin & Chiang 2012) that are assembled for the purpose of extracting the text in the torn documents, which it is an important process in the field of forensics.
Another application is the restoration of the fragments of archaeological objects, specifically ceramic and pottery fragments, which has been presented by several researchers (Leitao & Stolfi 2005; Smith et al. 2010; Oxholm & Nishino 2012) who were interested to find the solutions to broken fragmented pottery. Furthermore, numerous researchers (Toler-Franklin et al. 2010; Shin et al. 2010; 2012) have worked on the reconstruction historical wall paintings, which are usually scattered into many hundreds or even thousands of fragments, located in many sites, such as the seventeenth century BC fragmented wall paintings, excavated in Akrotiri, Santorini, Greece. In terms of the restoration of broken glass plates, the study carried out by Stanco et al. (2011) about the virtual restoration of the fragments of glass plate photographs of archaeological repertoires. This study focused on the methods that aimed to reconstruct the fragments of ancient pottery artifacts.

3- The Structure Search

In order to review previous studies, this paper concentrates on matching and reconstructing three-dimensional of historical pottery fragments. It divides the previous studies into four groups according to the period that the study has been prepared. For each group, all studies are classified based on the extracted features, the classification technique that was used, and the results achieved, as shown in Figure 1.

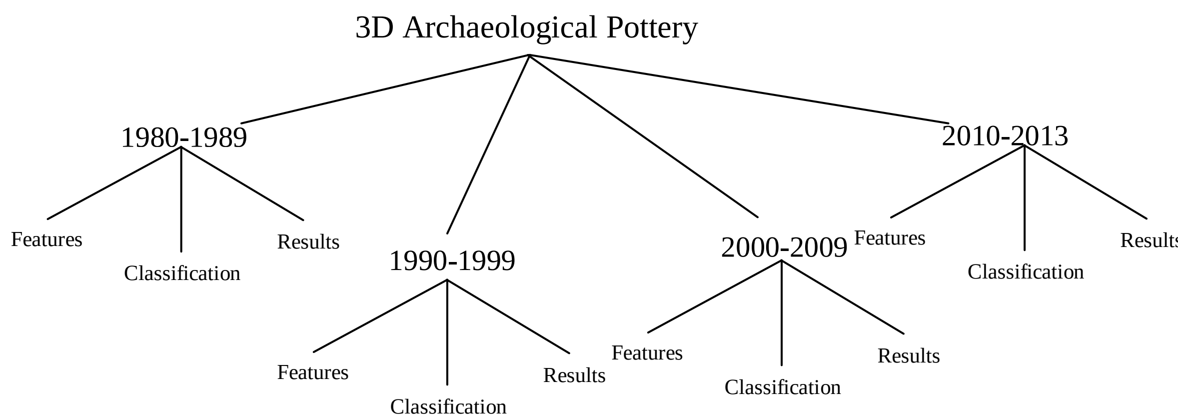

Fig. 1. The structure of the research.

4. Studies Performed: Since 1980 - 2013

This review summarizes all works implemented since 1980 up to 2013, and discusses the implications for classifying and reassembling artifact fragments. We would like to point out that this study focuses on pottery fragments only. The discussion of the involved studies is divided into four periods, according to the year the study was published:

4.1 Studies during the period in the 80's

In the mid-eighties, researchers were interested in systems that draw, archive, store, and retrieve the fragments that were excavated. In the field of reassembling objects, many methods have been presented to assemble jigsaw puzzles, and also to generate models of solid objects through using three-dimensional surfaces. Hall and Laflin (1984) describe the use of B-splines for shape representation. They exploited the idea that allows three-dimensional curved solids of revolution to generate curves based on B-spline curves, which fit the technique to generate object outlines and draw a profile of the pottery vessels. The advantage of this method is that it allows drawings of the 3D modeling of pottery profiles and compression prior to storage via computers for subsequent display and facilitates statistical analysis.

4.2 Studies during the period in the 90's

Attention of researchers began in the mid-nineties focus on the necessary solutions in the reconstruction of antiques. There are a number of research works that pertain to the field of automated restoration of antiques and bring them back to their original form. The most important studies are summarized and classified according to the type of image that has been obtained:

Through assuming that the pottery object is rotationally symmetric, Halíř and Flusser (1997) proposed a model to estimate the profile based on the archaeological fragment with high accuracy. The researchers proved that can estimate the parameters including the diameter and the perimeters of the object by identifying the radius of one fragment. Also, they proved that the intersections of the surface fragment with several parallel planes produce parallel arcs with different diameters and one axis. In order to form a circular arc, the fragment is placed in the correct orientation, which is estimated by expert archaeologists, so the intersection between the surface of the fragment and the projected laser plane generates the circular arc. The algorithm has been evaluated on both synthetic data and real pottery data; it achieved an error rate equivalent to 2-3 mm.

By adopting several shapes and partial information such as the rim and base of the fragment, Sablatnig & Menard (1997) proposed an automatic classification system for the reconstruction of full vessels based on the attributes of the profile's curvature, the subdivision of the profile between the rim, body, and the base (ring and flat). The researchers relied on the bottom-up design for reconstructing the fragments. The descriptive profile is formed when the profile is divided into the primitive elements and stored. They used a descriptive language to classify the unknown fragments by comparing its descriptive language with other fragments through calculating the graph similarity. Finally, the reconstruction of the object was achieved according to the highest similarities between the graph and subgraph.

Several researchers addressed the problem of reconstructing the fragments as matching the boundary curve instead of matching entire surface (Üçoluk & Toroslu 1999) introduced the automatic reconstruction of broken 3D surface objects by exploiting the outlines of the shapes to achieve the matching of adjacent contour pixels of two ceramic fragments, despite the loss of some of the fragments. Their algorithm includes a 3D object with closed curves and thin-walled fragments. The feature vector was extracted at each discrete boundary curve point of the fragment, in other words calculating the curvature and torsion scalars. In order to obtain the best matching, a Noise Tolerant algorithm was applied by using simulated broken objects. They match and align the vase fragments through a comparison of the broken surface boundary curves.

Halíř (1999) proposed an automatic estimation of the axis of rotation of archaeological pottery fragments based on geometrical properties. They exploited the fact that any ceramics are made on the wheel, and the horizontal section of broken fragments is in the form of a circular arc. Their approach consists of several steps to estimate the axis of rotation, which can detect the accurate estimation from the first step. It can be improved by applying the direct least squares optimization and by using the M-estimators method to obtain a more robust estimation. Sometimes there are influencing factors to estimate the axis of rotation, such as noise outliers and systematic errors. They address this problem by applying an iterative refinement of the estimated rotation axis by a robust circle and line fitting. Their approach was evaluated through using synthetic objects and real pottery fragments.

4.3 Studies during the period in the 2000s

This section gives a brief description of the most common research works that pertain to the field of automated and semi-automated reconstruction of archaeological pottery objects. In this phase, the work during about ten years was primarily centered on the estimation of shape models from 3D surface data. The research works are divided into two types, as follows:

An approach depends on surface morphology is presented by Papaioannou et al. (2000), which was aimed at the semi- automatic reconstruction of archaeological finds by exploiting their geometrical information. Their approach includes estimating the fracture side of the fragment depending on surface bumpiness by the depth buffer approach, and for the purpose of achieving matching, the system candidates the sides that were relatively bumpy. The error matching is computed for all candidate facets for every pairwise of fragments via optimizing the surface similarity error between two fragments with reference to their relative orientation. Finally, the reconstruction activity begins through governed basic rules, and was applied on the pairs of candidate fragments that have small matching errors. In order to improve the clustering process, other characteristics such as the material or prior structural knowledge is used. Their algorithm has been applied to synthetic and real data, and the result achieved 50% without material and structural constraints or user enforced selectively, and achieved 90% with constraints and user intervention.

Assuming that all the pots have an axial symmetry property, through the estimation of break-curves and profile-curves, Willis et al. (2001) created a framework for the automatic assembling of 3D pots by obtaining a 3D measurement of data of fragments. Therefore, the researchers depend on extracting the geometric shape information and its covariance, rather than using raw measurement-data of fragments to estimate the geometric parameters of the fragments, such as the vessel axis in standard position, profile-curve and z- axis, a portion of the outer surface, break-curves to whole pots, and 3D Euclidean transformations. In order to combine and formulate the geometric parameters, the authors applied a Bayesian method, where the search strategy reduces the comparisons of configurations that are not possible, and at the same time, it provides a strong computational method for aligning breaks curves and outer surfaces.

Schindler et al. (2001) have developed an automated classifying archaeological ceramic fragment system by depending on the profile. Therefore, researchers assumed that the object has an axial symmetry property and the profile can represent a closed curve in the plane. Hence, the researchers merged several methods of approximation and interpolation of the closed curve by using B-splines, because this function has the property of exhaustive approximation. After testing the method by using real and synthetic data, it achieved results through the graphical output and provided the best representation for the reconstruction of the fragments.

The framework for automatic assembly of broken pottery vessels was developed by Andrews & Laidlaw (2002). In this framework the match is achieved through a multi-feature, which includes comparing the features automatically to reconstruct vessels from a pairwise of pottery fragments. The researchers relied on the geometric relationships for matching pairwise fragments, and the evaluation of the probability of the matching according to the fragment position by using a $\chi 2$ -statistic. The result was obtained through the testing of eight groups that consisted of 16 fragments; their method achieved the correct reconstruction for only 13 valid pairwise matches.

Based on a Hough-inspired method that can estimate the rotation to orientate the three dimensional model, an automated system for classification of fragments by Mara et al. (2002) was developed. The classification of the fragments depends on the profile of the fragment, which represents the longest elongation on the surface of the fragment that is a parallel to the rotational axis through two points, and also depended on multiple measurements of the fragment, such as the diameter rim, diameter of the wall, height, and the characteristic ratio. Therefore, the authors estimated the profile of the fragment and the curvature points. This helps for segmenting the curvature into its primitives. The researchers tested their system to classify a total of 70 real fragments. Through the estimation of the rotational axis, they were able to classify 62 fragments successfully.

Through small fragments, it is possible to estimate the geometric structure for pots that have a symmetrical axis. This a robust approach proposed by Cao and Mumford (2002). The authors exploited the information of the surface of the revolution, where the maximal spheres that are tangent to the surface will be centered on the axis of symmetry. To estimate the centers, the authors calculated the line that minimizes the weighted least squares distance, and then estimated both symmetry axis and the profile curve. For the purpose of assembly of the pot from several fragments, the authors used estimations that depended on computing the confidence bounds for the axis and the profile curve by using bootstrap methods.

Papaioannou et al. (2002) proposed an automatic 3D reconstruction based on the matching and alignment of parts. The authors focus on the surface geometry, so the matching was performed directly through the plane between two arbitrary fragments, where the distance was calculated between the mutually-visible faces of the fragments by utilizing the 3D points of the whole surfaces for pair fragments. Afterwards, they computed an error measure between the distances for both of the two faces of the fragments, and minimized the distance between the 3D surface points of the two fragments by using the standard global optimization scheme. During the z-buffer method, the matching error was computed, and minimized this matching error for the purpose of obtaining the best fit between the objects. They tested their method on the digitized models of real fragments and the results achieved matching the fragments with constraints or without constraints.

Willis et al. (2003) presented a method for automatically estimating the axially symmetric surface geometry of pot fragments and reconstructing the three dimensional fragments by depending on the estimation of both the axis and the profile curve for every small fragment of the archaeological object, through computing the axially symmetric algebraic surface. Also, the authors relied on axially symmetric implicit polynomial surface models to extract a geometric model, and the error was analyzed statistically. The authors applied their method by testing five fragments selected from Petra, Jordan. In order to enhance the robustness of their method and remove the noise that was caused by the measurement errors, they used a bootstrap algorithm that included a set of information for each fragment, such as a covariance matrix for axis parameters.

A fully automated system for the reconstruction of pottery fragments depended on the profile of the fragment was an approach proposed by Kampel and Sablatnig (2003a). The core idea of this approach is to find the original form of the pot through one fragment and assemble the fragments without manual intervention. In order to classify the fragments, the authors focused on the estimation of the correct orientation and the profile of the fragment. To achieve the reconstruction stage, the authors depended on the partial similarities of the profiles, and the pots were assembled on the basis of the description of the data stored. Their method has been tested on 40 pottery fragments, and the result it achieved was 50% successful. Note that it has discarded 18 fragments due to the wrong estimation for the axis of rotation. In the same year, Kampel and Sablatnig (2003b) presented an automated archival, classification, and reconstruction of archaeological ceramic system. By depending on both the front and back surfaces of the ceramic fragments, the features are extracted automatically by computing the profile, and the measurements such as the ratio of the fragment area of an object and both the dimensions and diameter of the object. Their approach requires prior knowledge to the type and class of the object, and also an estimation of the correct orientation of the fragment for the purpose of determining the exact position of a fragment according to the original object. By using the mathematical curves, the fragments are classified depending on cubic B-splines, and their methods achieved a success value of 50%.

A semi-automatic system developed by Melero et al. (2003) for the 3D reconstruction of Iberian vessels by estimating the orientation of the fragment, computing the symmetry axis, and detecting the profile. In order to estimate the correct axial angle of an orientation fragment with the aim of extracting a vessel profile, the authors selected the genetic algorithms because it is a flexible approach and make the method more robust. Through simulating the method of archaeologists and relying on some measurements, such as the estimation of the diameter at different heights, rim angle, orientation of shape, extracting the profile and drawing of the fragment, it can classify the vessel fragments according to rim-fragments. Therefore, by using the 2D drawings of synthetics and the real fragments to reconstruct Iberian pottery, the system could reduce the error margin to 60%.

A complete framework was proposed by Willis & Cooper (2004) to automatically assemble pots from three-dimensional fragments, taken into consideration that the pots are axially symmetric. The geometric information was extracted, which included the symmetric surface axially, the axis of the vessel, the fracture curve and 3D Euclidean transformation. The authors assumed three assumptions, the surface measurement points which distributed Gaussian normal distribution, surface measurement normal distributed circularly symmetric Gaussian perturbations on the unit sphere, and the break-curve measurement points that are distributed spherically symmetric Gaussian. Through applying the Maximum Likelihood Estimation, the system obtained the ability to assemble the fragments. Afterwards, the authors applied a Bayesian approach to formulate and merge the four parameters previously mentioned, and the result that was obtained was the assembling 10 of the 13 fragments belonging to one pot.

Reassembling rotationally symmetric archaeological fragments is a model proposed by Kampel and Sablatnig (2004). This approach was carried out by determining the correct alignment of the fragment that represents the right position for the original vessel. In order to classify the fragments, the features were extracted based on the profile section and the absolute measurement such as color, surfaces and type of material. The matching process has been done by primitives and relations between the fragments. The authors proposed an approach for a matching algorithm relying on the point-by-point distance between facing outlines. Their algorithm was applied by the utilization of a synthetic pot that consisted of five parts, and one rim and two wall fragments. Matching results have been achieved in some fragments and failed in others.

A fully automated approach has been proposed for the reconstruction of archaeological thin pottery based on concentric circular rills. It was proposed by Kampel et al. (2005). Their algorithm begins through defining the inner side of the fragment, and sometimes the other side which contains rills, then the surface of the fragment is segmented into upper, medium and lower curvatures. The orientation of the fragment is estimated and the classification process is based on external points and estimate the oriented profile. They tested their method by using 35 fragments of a small size and the lower curvature.

Based on the technique of implicit surfaces and Genetic algorithms for automated pottery classification approaches, a method was presented by Maiza & Gaildrat (2005). The main idea is the classification of three dimension archaeological fragments pots, by computing the distance between the tested model and the position of the specified fragment. Therefore, the features that are used in this work depended on the profile of the object, which includes the position and the orientation for each fragment. In order to reduce the distance between two pottery fragments and to find the perfect location based on profile computation, a genetic algorithm was applied and obtains the best match. Their approach was applied to 100 individuals, including three types of fragments (high, central and low).

A more sophisticated method than the previous in the adoption of the axis of rotation to determine the direction of the fragment was adopted by Mara & Sablatnig (2006), where they noted that previous methods require the object be symmetric and complete as well as including manual interaction. Therefore, they presented an automated system to discard the manual interaction when the profile lines are extracted through dependence on circle templates. In order to estimate the rotation axis, the authors implemented their method by using synthetic fragments in different shapes and small sizes and applied the method on real well-known vessels. Hence, the results that were achieved in relation to the fragments of the object were that the method was able to orientate 24 fragments out of the 25, while applying the method on a set of 24 synthetic fragments such as a cylinder, cone, sphere and s-shaped object. The method achieved a small amount of errors. A method based on region features instead of points to automatically reassemble

3D solid objects was introduced by Huang et al. (2006). This technology includes the application of the segmentation algorithm based on the graphcuts method for the purpose of spotting the potential surfaces for the fragment; in this case, the authors computed the boundary of the fragment edges on each face to identify fractured regions. For the purpose to classify the faces of the fragment, the authors checked the roughness of the fragment faces, and then generated clusters of feature patches for alignment based matching. The features in this work are characterized by clusters and overlapping. The matching process between the fragments of an object generates a set of possible matches. In order to successfully carry out the reconstruction the object, global multi-piece matching was computed, and a local multi-piece registration was performed at the same time.

Depending on some numeric measures, Igwe & Knopf (2006) used a multi-variable technique for clustering the fragments automatically, and using unsupervised learning self-organizing feature map (SOFM) algorithm, the fragments are aligned to achieve matching. They exploited the topological structure and established the lattice spherical mesh with triangular elements based on a three dimensional SOFM. To deform the node locations and spherical mesh, each node is given by the weight vectors of elements. The reconstruction process selects the largest fragment to be the target and are assembled with the rest of the parts that have a similar geometry; the objects that are assembled using this model do not possess specific geometric features, but depended on data points from each piece. A study that was focused on assembling thin artifact fragments by obtaining 3D geometric data was presented by Zhou et al. (2007). The authors relied on external and internal contour features, which are extracted from the boundary edges of the fragment by using a multiplicity of edge method. After that, polygonal arcs of a triangular shape are analyzed and a matching algorithm was implemented based on junction vertices. In order to make the matching algorithm quick and easy, the authors reduced the problem of matching from three dimension polygonal arcs to one dimensional numerical string, and the reconstruction process was represented as a root of a binary tree, and the fragments were represented as nodes. Also, they treat the problem of holes and seams through removing the redundancy triangles, and by generating suture lines, linking all vertices.

Other approaches for automatic assembling of fractured objects that are based on the interaction of archaeologists for reassembling artifacts was proposed by Lu et al. (2007). Their approach consisted of the transfer of the boundary of the fragment into curvature and torsion that represents features, and then applying the cyclic edit distance algorithm, to achieve the matching process between the two fragments. The boundary of fragments was displayed to the archaeologists, and through their experience, they selected the fragment which is the most probable to be reconstructed with the other.

One of the works that exploited the edge of a geometric object to match three dimensional fresco fragments was proposed by Brown et al. (2008), who offered an automatic system for computer-aided documentation and reassembly of Theran Wall Paintings. Their method includes capturing a virtual 3D model of each fragment along with high-resolution color and texture information of the front surface. By depending on the shape information on the side of the fragments and color, plaster surface texture, and surface roughness information, the method attempts to fit pairs of fragments. The results indicated that the proposed algorithm to match the fragments has achieved high results when using a ribbon matcher, which depends primarily on the edge of the geometry and the decorations continuity of the fragments.

4.4 Studies from 2010 till to 2013

In order to highlight the most important studies that have addressed the problem of reconstruction of pottery fragments within the phase between 2010 and up to 2013:

Through two theorems of mathematical formulation, Arabadjis et al. (2010) presented a methodology to reconstruct three- dimensional solid objects. Their method relies on selecting one fragment randomly that was considered a fixed fragment, and as the axis of its center was located on the z -axis. The selection of another one was considered to be the rotator fragment, which is a random orientation around its central axis, as well its position is random as well. By exploiting the boundary of the fragments and the application of the mathematical criteria, the researchers were able to achieve the matching between wall-painting fragments, even when there were gaps between the fragments, which matched at a rate 50 times of complete matching. For the restoration of Yao Zhou's famous porcelain, Zhou et al. (2010) presented a method for estimating the profile and symmetry axis. To briefly review the method, the rotation axis of the symmetric surface were estimated by relying on the Pottmann and optimization method, and then calculating the full profile of the pottery fragment by assembling neighboring fragments through matching features of the various fragments. Also the researchers used texture mapping for the purpose to obtain the pottery model more realistically.

One approach that merged multiple match properties into a scoring function by using machine learning was presented by Toler-Franklin et al. (2010). In order to extract features from the database, the authors used three forms of the database, which were color maps, normal maps and 3D meshes. Based on the differences between the calculated properties of patches, the classifier was trained to score patch pairs. Depending on the normal maps, the authors focused on evaluating the discriminability of their new patch properties. It was noted that the authors were provided with three new features for special cases. The normal-based features that depended on the fragment when the color varies from one location to another, sometimes the fragment was exposed to erosion, and sometimes the fragments contain different types of brush strokes. Therefore, the researchers have relied on extracting features through calculating the min values, mean values, max values, and the standard deviation values for each feature. The authors conducted classification experiments on three datasets of fresco fragments. Their method achieved a correct percentage of the features selected by 90%, and non-match 78%.

As a result of the combined experience and feedback of archaeologists and the use of 3D convex hull technology with vessel surface markings, Cohen et al. (2010) formulated a generic vessel model. Their work consists of extracting 3D convex hulls for each fragment from surface markings, which was extracted by using color information. Through all points on the marking, the matching procedure was done depending on absolute affine invariant moments, where matching was achieved through a predefined threshold value. The first tests for this method of the dataset consist of three ceramic vessels that having surface markings. The amount of the residual alignment errors was in the range between 1.34 x 10-5 and 4.56 x 10-1 when using a nonlinear quadratic map for each fragment and generic vessels. In the case of the use of a global affine map, the amount of residual alignment errors was in the range between 0.8 to 15.6 for fragments and generic vessels.

Karasik & Smilansky (2011) proposed a technique based on profile morphological analysis for the classification of ceramic. Their method depended on the mathematical representation of the profile for ceramic fragments on the basis of three functions (radius, tangent, and curvature). The authors employ the Cluster Analysis (CA) method to cluster and classify the fragments by using Discriminate Analysis (DA). The proposed algorithm has been applied on 358 fragments to reconstruct five types of vessels, and the results showed that the fragments were classified correctly 94.8%.

In order to determine the pair of candidate fragments for matching fragments depending on the threshold, an automatic method was presented by Funkhouser et al. (2011). It combines two previous ideas from Shin et al. (2010) and Toler-Franklin et al. (2010). Their method includes creating the classifier based on many properties extracted from the fragments match such as contour and ribbon, junction angle and others, for the purpose to achieve accurate expectations for reconstruction of fresco fragments. They selected the training set, and chose a classification model that was built from the training set, which depended on M5P regression trees. It then estimated the accurate probability for new candidate matching between a pair of the fragments, and the classifier become a trainer. By training a machine on the three datasets taken from different regions, the results indicate that it is possible to train the classifier for matching a dataset depending on its properties, and then used it for the purpose of prediction matching from another set.

Belenguer & Vidal (2012) suggested an automatic technique for the reconstruction of 3D archaeological flat fragments based on the Graphics Processing Unit (GPU) Depth Maps technique. The proposed technique determines the fragment characterization based on a projection that was calculated through the graphics processing unit, and that reduces the complexity of the comparison between fragments. The distances on the surface of the fragments can be measured via the orthographic projection matrix, and this can be determined through the angle of the plane. A search algorithm is then applied to obtain the alignments between fragments. By employing the hierarchical search technique, it obtains the optimal solution for the problem of storage in memory. In order to reduce the pre-processing time and improve the efficiency of calculating the best displacement, the technique of hierarchical displacement is applied.

Contrary to previous methods, some works did not rely on the border models or mathematical surfaces, but rather relied on the silhouettes method, such as Kashihara (2012), who suggested an algorithm for the automatic reconstruction of three-dimensional artifacts from fragments quickly and with high accuracy. The study focused on the development a Hybrid Genetic algorithm because it is important for defining the approximately spatial position of 3D fragments and reduced search spaces. To regulate the positioning of 3D fragments, a hill-climbing method was applied and the features were extracted by using the speeded up robust features (SURF) technique. Therefore, in this case, the fitness function is evaluated to determine the correct positions of fragments. The author executed the experiment on a vase that consisted of five fragments. Through the design of a user interface, this enables the archaeologists to reconstruct the archaeological fragments.

An efficient solution for the automatic reconstruction of three-dimensional Wall-Paintings introduced by Papaodysseus et al. (2012), where they define the dataset through the surfaces of the upper, lower, sides, and the central axis of each fragment. In order to get an accurate match, the authors performed a procedure to rotate the fragment on its central axis at a very small angle around the fixed fragment, which was selected randomly. At the same time, the probability of contact between their surfaces was determined. There are four criteria are applied in each placement to test the matching. The first criterion involves examining the relative lengths of the curves of the upper surfaces to the joint between two fragments that were potential matching for the purpose of reaching a suitability match. In the second criterion, the connection between the fixed fragment and the fragment that revolved around it might obtain some local overlap, so this criterion prevents overlap through the use of a threshold. The third criterion deals with contact surfaces, and used a theory that had been proved by the authors. The last criterion was checking the length of the contact curve between the two fragments that had a potential matching, and the matching was achieved when the volumes of the fragments are less than the threshold that has been estimated previously. The proposed method was applied to the 41 fragments that were taken from different islands and has achieved a success rate in some cases by 100%, and did not achieve matching in other instances. Son et al. (2013) proposed to solve the problem of the automatic restoration of three thin clay pots, mixed with each other, or in case of presence of gaps. The authors relied on the geometric structure of the object and the way the fragment was broken. They considered that the object was axially symmetric. They solved the problem by exploiting the two approaches that took advantage of the local and global geometric structure, and their methods include estimating the accurate Axis of symmetry Profile Curve (APC) for each fragment by using circle templates. The classification of fragments was separated into four types depending on the criteria sufficiency and distinctiveness that was done, and the matching of the fragments that have characteristics of symmetry were also implemented. Other algorithms were applied in the absence of the symmetry properties of the fragments because they were small, flat or spherical. These algorithms were based on extracting the feature points from fractures curves. The system was able to reassemble three pots consisting of 48 fragments during 10.56 hours by using the Intel Core i7 processor.

5- Analysis the Results

A variety of algorithms have proposed methods to reconstruct the archaeological pottery fragments. This paper is interested to analyze the most successful research works that were implemented in the period between 1980 and 2013. In particular, those who have worked in the field of reconstruction of three-dimensional pottery fragments, and several works focused on the field of solid objects, such as Hall and Laflin (1984), Huang et al. (2006), and Arabadjis et al. (2010).

Table 1. Demonstrates Studies Performed during 1970 -2013

Study period	No. of Study
1980-1984	1
1995-1999	4
2000-2004	13
2005-2009	8
2010-2013	9
Total	35

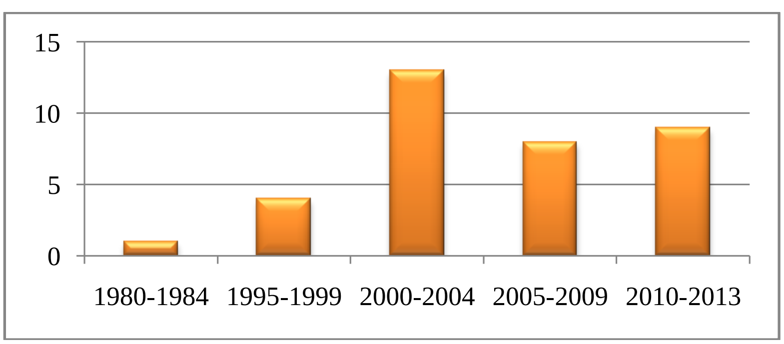

Fig. 2. Demonstrates the Studies Performed Since 1980 - 2013

As shown in Table 1 and Fig 2, there are a few studies that are interested in reconstructing the fragments in the eighties. The researchers focused on the archiving, documentation, drawing, and storage of thousands of broken fragments that have been excavated in a numerous locations. So, they exploited the computer for creating a large database to facilitate viewing and accessing information quickly. We would like to point out that the authors began their interest to find solutions for reassembling fragments of objects during the last three decades; especially in the 2000's and onward.

It turns out that most of the studies suggested an automated system, except the few studies that required intervention by the archaeologists to take a decision for the reconstruction of fragments, i.e., semi-automatic systems such as (Melero et al. 2003). Therefore, automatic methods were used to increase accuracy.

Additionally, this study focused on most of the features that were extracted for the purpose of reconstruction of archaeological pottery fragments in the previous research works. Most of these research works followed to estimate the profile that includes the details in Table 3; in particular, during the 2000s, the authors focused on the geometric surface in order to obtain the clustering and matching of the fragments, and sometimes also the edges, such as contours, outlines and boundaries. Table 2 and Figure 2 show that the authors reduced their dependence on profiles during the period from 2010 to 2013, and focused more on color and texture to extract features.

Table 2. Shows most of the Features used in articles during the period 1980–2013.

The study period	Features extracted	Number of articles
Studies in the 80's	-B-Spline curves	1
Studies in the 90's	- Geometric. - Outlines of the shapes.	2 1
Studies in the 2000s	- B-Spline. - Boundary of the fragment - Profile.	1 2 18
Studies from 2010-2013	- Color. - Edges. - Profile.	2 2 4

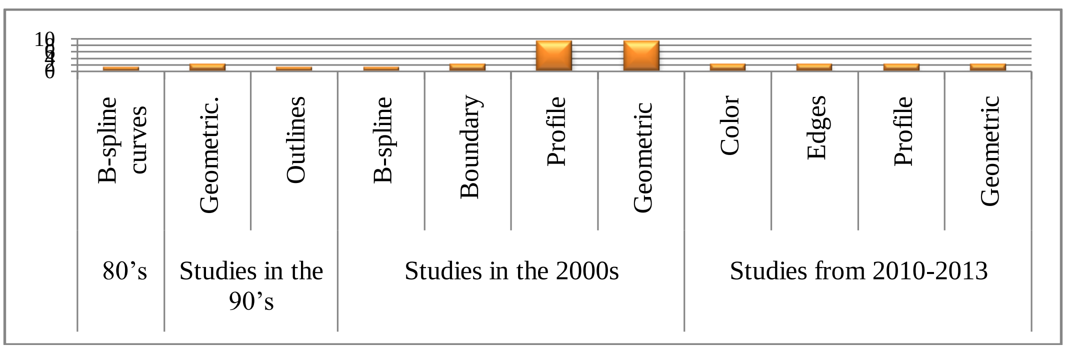

Fig. 2. demonstrates most of Features used in articles during the period 1980–2013

Table 3. Shows the details of the Profile that estimated.

The study period	Profile
Studies in the 80's	- Outlines.
Studies in the 90's	- Estimate the parameters such as diameter and the perimeters of the object - Axis of rotation .
Studies in the 2000s	- Estimating the fracture side or break-curves - Estimated the curvature points and the rotational axis - Symmetry axis - Axial angle of an orientation of the fragment - The measurements such as the ratio of the fragment area of an object and both the dimensions and diameter of the object
Studies from 2010-2013	- Rotation axis of the symmetric surface were estimated - Radius, tangent, and curvature - Estimating the accurate Axis of symmetry Profile Curve (APC)

In order to highlight the most important techniques that the authors adopted over the past decades about the classification of archaeological fragments in the light of extracted features, and reconstruction into their original form. Table 4 shows most of the techniques that have been used it to implement the classification and matching process.

Table 4. Shows most of the Classification and matching technique used since 1980 until 2013

The study period	Classification	Matching
Studies in 90's	- Descriptive language	- Highest similarities between the graph and sub-graph. - Noise Tolerant algorithm.
Studies in 2000s	- Genetic algorithms. - Self-organizing feature map (SOFM) algorithm.	- Governed basic rules. - Bayesian method. - Evaluation of the probability a $\chi 2$ -statistic. - Computing the confidence bounds for the axis and bootstrap methods. - Minimized the distance by the standard global optimization scheme. - Partial similarities of the profiles. - Maximum Likelihood Estimation and Bayesian approach. - Point-by-point distance. - Global Multi-Piece. - Rest of the parts that have a similar geometry. - Matching algorithm was implemented based on junction vertices. - The cyclic edit distance algorithm.
Studies from 2010-2013	- Based on the differences between the calculated properties of patches. - Discriminate Analysis (DA). - M5P regression trees. - Distances. - Hybrid Genetic algorithm.	- Fixed fragment, and rotator another fragment random orientation around its central axis. - Assembling neighboring fragments through matching features. - Absolute affine invariant moments. - Graphics Processing Unit. - Four criteria are applied in each placement to test the matching. - Criteria sufficiency.

Through the review of the mentioned studies, it was found that most authors relied on synthetics and the real fragments to apply their proposed algorithms. Some authors relied on the Genetic algorithms classifier such as (Melero et al. 2003; Maiza & Gaildrat 2005), the result that (Melero et al. 2003) have achieved reduced the error margin to 60%. (Karasik & Smilansky 2011) have applied Discriminate Analysis, and achieved a success rate of 94.8% by using a database of a total of 358 fragments to test their model. It turns out that the proposed solutions to the classification technique is still not meet the ambitious.

As for the match and reconstruction methods many researchers proposed different methods, for example Sablatnig & Menard (1997) relied on highest similarities between the graph and subgraph; Whereas Üçoluk & Toroslu (1999) depended on Noise Tolerant algorithm. The previous studies through period 2000 to 2009 relied on statistical methods to reconstruct the fragments to the original form such as Willis et al. (2001); Andrews & Laidlaw (2002); depended on Bayesian methods, evaluation of the probability a $\chi 2$ - statistic respectively. Also the previous studies depended on mathematical methods such as Papaioannou et al. (2002); Kampel and Sablatnig (2004); relied on minimized the distance by using the standard global optimization scheme, and point-by-point distance.

Whereas Zhou et al. (2007) reconstruct the object by employing fragments matching algorithm, that was implemented based on junction vertices. Finally, (Papaodysseus et al. 2012; Son et al. 2013) the highest approximate results achieved in some cases by 100% when applied spatial criteria in each placement to test the matching.

CONCLUSION AND RECOMMENDATIONS

One of the main challenges is the reconstruction of fractured archaeological artifacts through a large number of fragments that are excavated, and finding the correct matching between them. In this paper, we attempt to summarize most of the previous research work for the purpose of facilitating new proposed methods, and to find the necessary solutions for the classify and reconstruction of archaeological fragments. We conclude that the previous computer methods for this task relied on the geometric features in the case of three-dimensional models, and the authors relied on the estimation of the profile, which includes the symmetry axis and orientation of the fragment. Nevertheless, use of the profile decreased during the period of 2010 to 2013, where researchers instead focused on other features such as the color and edges.

On the whole, the computer assists in reconstructing the archaeological fragments accurately and reassembling them to the original form in a two-stage process involving classification the fragments into groups and reconstruct. We conclude that the researchers focused on reconstructing the object without classification the fragments into groups, note that the artifacts normally are found in a fractured state and mixed randomly, and the process of manual classification may require a great deal of time and tedious work. Hence, it is important to come up with a solution for the classification of the archaeological fragments accurately into groups and reassembling each group to the original form by using computer techniques.

Additionally, we concluded that numerous studies depended on the principle component analysis method (PCA) to speed up the computation process and maintain most of the information, and also to select the best features. The other observation in most of the studies is that the reassembly of fragments adopted statistical methods, geometrical properties across fracture surfaces, the mathematical criteria and surface morphology. Also, some systems relied on archaeologists experience, and most previous works have focused on pairwise matching between two adjacent fragments by aligning fragments in fractured edges. Also, they usually exploited one feature without using the combination of many features, i.e., combining between the fragment structure that is divided into two main parts, shape features, and properties of the fragment, for the purpose to obtain the best classifiers.

In the future, more details about the contents of the studies must be mentioned in order to formulate a large database that may be a reference for researchers working in this field.

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