Why the Application of a Gaussian Curve and Seriation Programs can be Detrimental

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Abstract

Certain attributes are indicative of "chronological groups" while others are indicative of other phenomena. Any attribute may be characteristic of a specific group or not. It cannot, however, be slightly less or more characteristic of a group. Recognition of this situation highlighted problems with the application of the Gaussian curve within seriation programs. The problem of classification is no longer mathematical, but rather hermeneutic. The Bajuwarian cemetery at Altenerding proves that chronologically sensitive attributes occur more or less simultaneously. Here we are faced with a continual process of change that is sometimes faster and at other times slower: sometimes changes are more frequent and at other times sporadic. This is also why algorithms for the seriation of material finds, which anticipate that chronological groups do exist, and, as a rule, follow successively one after another within the context of their respective chronological types, cannot provide adequate results.

Key words: Gaussian curve, seriation program, chronology, archaeology

The practice of resolving chronological questions with the aid of seriation programs, whose algorithms frequently postulate a distribution of material finds through time in the form of a Gaussian curve, is still quite popular. Whilst analysing the Bajuwarian cemetery at Altenerding (Sage 1984), I chanced upon results that impugn the use of the Gaussian curve and seriation programs for such purposes.

The 1530 graves of Altenerding could have been classified chronologically with the aid of those material artefacts that are temporally well defined, such as arched bow fibulas in female graves and belt buckles and belt fittings from male graves. On the other hand, I was tempted to establish, with the help of stratigraphic tables, an entirely independent relative chronology, which would ultimately be furnished with absolute dates. The two principal objects used within the analysis were beads, the most frequent artefact in female graves, and belt buckles, the most frequent artefact in male graves. As the latter are also present in female graves, a correlation is proffered in the composition of beads from female graves. From the database, I extracted the attributes of both types of artefacts and initiated their classification through the KOR seriation program, written specially by Tomaž Zwitter (Pleterski and Zwitter 1993). While resolving questions of the delimitation of seriated groups, we also discovered that the groups in the combination tables and the tables of the seriation program in no way demonstrated simply a seriation of the artefacts through the course of time, but much more.

The problem was reconsidered on this basis. It was felt that the phenomenon of "non-chronological groups" was the consequence of a poor initial selection of attributes. That is, certain attributes are indicative of "chronological groups" while others are indicative of other phenomena. Any attribute may be characteristic of a specific group or not. It cannot, however, be slightly less or more characteristic of a group. Recognition of this highlighted problems in the use of the Gaussian curve upon which seriation programs are based. The problem of classification was felt to be no longer mathematical but hermeneutic (cf. Pleterski 1996). A table of stratigraphic relationships facilitated chronological interpretation. I decided to use 270 graves with absolute dates, which Hans Losert attributed using the chosen analogues, for additional control.

An unexpected result derived from this process. My six groups of belt buckles were indeed bounded quite narrowly chronologically, and they were thus truly "chronological groups" in this respect. However, they were not arranged in chronological succession. The groups chronologically overlapped in part, or were even entirely contemporaneous. This observation was confirmed by the subsequent dating process, after which I was able to determine 154 chronologically sensitive attributes.

It is evident that chronologically sensitive attributes may occur more or less simultaneously. Change and novelties arise continuously over time. Consequently, division into chronological levels is unrealistic and misleading, particularly as this leads to the creation of artificial divisions which simply confirm the preconceived slices of the chronological "sausage".

The graphs presented demonstrate that the majority of novel chronologically sensitive attributes appear between 550 and 600, and that the majority disappear between 600 and 650. The reason for this is that the majority of attributes from this period correspond to multi-part belt fittings. Were the attributes classified differently, the graphs, with respect to the appearance and disappearance of chronologically sensitive attributes, would also be altered. However, the partial contemporaneity of these attributes would remain.

If I were to provisionally define chronologically classifiable artefacts as "chronological types", then it follows that chronological types do not exist within the context of a single "chronological level" simultaneously, or successively (one after another) in further "chronological levels". In reality, we are faced with a continual process of change that is sometimes faster and at other times slower. Sometimes change is more intense and at other times it is sporadic. However, this is all it is. Each "chronological level" is actually an artificial definition. This is why all algorithms for seriation of material finds which anticipate that chronological groups

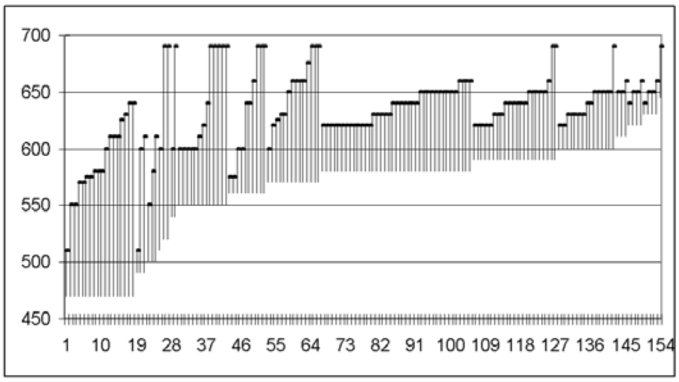

Figure 1: Chronologically sensitive attributes, in order of their succession, showing the temporal range of appearance of attributes within graves.

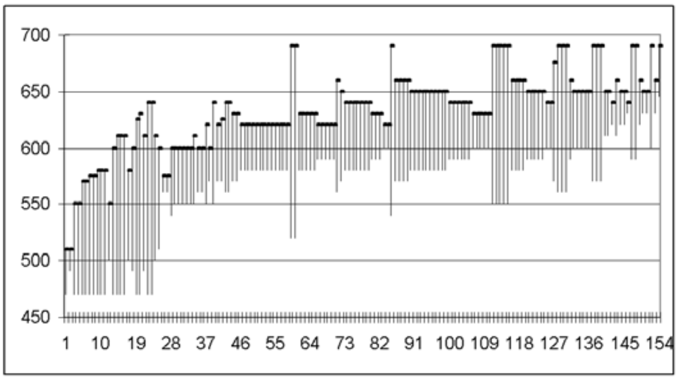

Figure 2: Chronologically sensitive attributes, order by succession and by median temporal range of attributes within graves.

do exist and, as a rule, follow successively one after another within the context of their respective chronological types, cannot provide adequate results. Occasionally analyses may apparently succeed. Despite this, such results could still not be used as a reliable tool. However, they do remain useful tools for searching for congruent structures. I rest assured that I am not alone in my thoughts on the basis of a lecture by François Djindjian; who emphasized that the understanding of an artefact is a question of proficiency and not a characteristic of computer analysis, that semiotics can be more valuable than taxonomy, that seriations are not necessarily a reflection of chronology and that chronological structures must be separated from other relevant factors (Djindjian 2000).

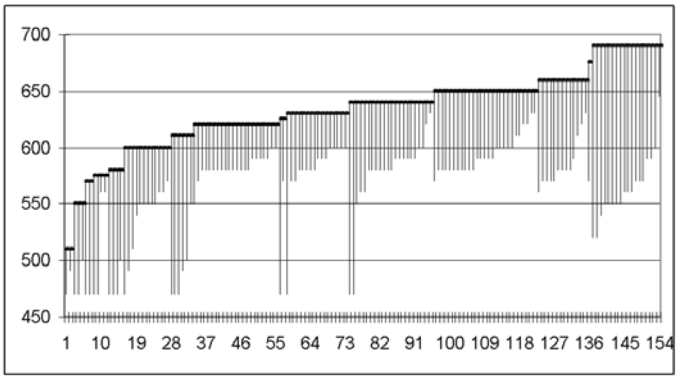

Figure 3: Chronologically sensitive attributes, in order of their succession, showing the temporal range of the disappearance of attributes from graves.

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Quantities, Possibilities and Probabilities: Some Experiences from the Research of the Roman Age in Slovenia

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Abstract

The paper considers the state of Roman ceramic studies in Slovenia. It questions the legitimacy of current approaches to ceramics, outlining problems in procedure and placing contemporary practise within its historical context. The range of archaeological uses for ceramics is considered and suggestions are made for the extension of ceramic studies using data from the urban area of Emona and a number of Roman cemeteries in Slovenia.

1. Introduction

Knowledge of how often we are able to detect specific objects or features within an individual archaeological record, within a particular findspot or within a specific (larger or smaller) geographical unit, has always been a very important component of archaeological research. It is often the basis on which conclusions are reached. In the language of theoretical archaeology, it could be said that the statistical method of previous developmental phases in archaeology permitted the development of archaeology. The computer has opened undreamed-of possibilities for contemporary research procedures. It would therefore be advisable to recall experience of previous decades. Such examples could help, to some degree, to establish what types of questions should be framed and what the product of research might be. I am, of course, discussing this matter on the basis of my personal experiences, and the literature cited might appear one-sided at first glance - but I am listing here only those of my reports which substantiate these observations.

These experience relate to the Roman Period in Slovenia. This period is, more or less, identical to the duration of the Western Roman Empire, as it is generally known. It is, to a certain extent, a specific period; a range of written sources provide evidence concerning the circumstances of the Roman Empire. Consideration of the data enables the construction of a material world with a number of common features, allowing the application of analogies between distant places. On the other hand, this huge state retained many local characteristics. Moreover, substantial distinctions existed among the small but diverse regions of our country, located in what was, at the time, an important Northern Adriatic - Eastern Alpine passage to the continent. These distinctions are noticeable from the time of annexation. From the time of the late Republic the littoral zone became a part of Gallia Cisaplina. Most probably the majority of the western part of Illyricum became a passable corridor at the time of Augustus' first expeditions into the Adriatic hinterland. The Alpine part, however, was not formally or legally organised as a province before the time of Claudius. These, along with many other undisputed facts, influence and continue to influence, the problems we wish to research.

2. The pottery

This is the field in which I have most experience. The statistical analysis of ceramics, although previously conducted on the basis of piles of hand written slips of paper subsequently became a component part of the new systematic excavations undertaken after World War II (Horvat M. 1999). The opportunity to publish all finds, along with the entire process of analysis, were far more limited in the past comparison with the situation today. Yet even today the result of much analysis can be presented only in short reports at professional meetings, frequently only to specialists. J. Horvat's (Horvat J. 1999:233) important discussion of analyses based on numeric studies of ceramics, was published in RCRF Acta. Here she comments on the lack of evaluation of criteria and methods used for obtaining comparative data, and this paper serves as an important introduction to this report.

On any occasion when experts from various specific fields meet, it would be in order to dedicate a few words to our established practice of estimating the *number of individual vessels*, from fragments found in individual archaeological contexts or groups. This practice has been introduced, with slight modifications, into our country following its general international use and has, in my view, contributed to the construction of a basis for statistical investigation. I am convinced that this practice is still applicable, all the more so since its completion is accelerated by the use of computers. Over and over again we find ourselves confronted by the task of "translating" the number of fragments into numbers of vessels. Any two results are hardly ever identical and an entirely reliable method is still not available. Even today, none of the detailed research (technical, chemical, etc) of substance and shapes, aimed at achieving this purpose, has been adequately published. Macroscopic analysis, which had been in use from the very beginning of modern archaeological research, still forms the basis for this work - but it demands considerable practice (few hours of practical work in a restoration workshop is the precious source of necessary experience!) and, of course, the time to ponder over it. Almost 90 % of the Roman ceramics found in our country are made on the potter's wheel (in 80 % of cases on a fast wheel) and fired in closed kilns. This manufacturing technique gave the products a unity of surface; but not without exception. Although the product of specialised manufacture, each vessel is to a large extent the result of handicraft and these vessels almost never have the same texture around the entire circumference. They are not equally fired, etc. We must point out that the final, or specially moulded parts of vessels, like the handle or the rim, are almost always slightly different in texture, since intense kneading extracted the larger particles and inclusions from the clay. The question whether several fragments belong to the same or to a different vessels can most easily be resolved in cases of fragments of moulded terra sigillata: this knowledge forms the basis of all the analyses aimed at following the spread of sigillata from southern, middle and eastern Gaul. Work with atypical surface fragments of plain sigillata is only slightly more difficult (a higher percent of errors might occur, although with experienced researchers these errors do not exceed 10 %), if accompanied by a sufficient number of distinctive parts of vessels, stamps, sections of rims and legs. The same holds for all sorts of semi-industrial pottery, manufactured in larger workshops. In comparison , the error margin for handmade local pottery can reach up to 30-40 % of studied groups!

We never place enough emphasis on the importance of possessing sufficient knowledge of other, previously excavated material from the same site or at least from near-by sites. It is easier to define *shapes* of particular vessels, and these are usually the first to be determined. We therefore arrive, relatively quickly, at the conclusion that amphorae, jugs, plates, pots, etc. can be found within a specific group. The decision on what *function* the individual artefact actually served usually demands additional interpretation: there are particular shapes for specific uses of pottery, which more or less serve the same function at various locations, and then there are other shapes which might have been used for a range of functions, although of course, we cannot exclude the possibility that an old and damaged sigillata cup could have occasionally been used for other purposes (as is often the case today!), for instance for mixing paint or glue. My experience tells me that the conclusion about the use of the vessels from an individual archaeological complex, can in most cases only be reached towards the end of the study. Nevertheless, the terra sigillata or other distinct earthenwares, as well as amphorae and mortars, represent exceptions, due to the fact that their function is usually very clearly defined.

The result of any investigation is therefore determined, above all, by the character of the archaeological group and by the stratigraphic record of the ceramics. For this reason I feel it important to emphasise the necessity (even within a large team, where tasks are very clearly divided among experts) for professionals dealing with the investigation of particular materials to have a good overview of the situation in the field. I believe that I was able to form my conclusions about pottery from several excavation sites within the city walls of Emona because I recorded most of the ceramics immediately as they appeared from the ground and was thus able to examine details while the trench was still open. Even when first recorded it was clear from where material originated, e.g., from the stratum later covered by the pavement of the next building phase and from garden humus. These data were later augmented by all previous data and by the overall results of the excavations, corresponding buildings or other components of the settlement structure.

The material records stored during the excavation used to be the quickest procedure for *dating* an individual stratum or archaeological complex. I suppose it is unnecessary to waste words about this procedure for this particular group of readers. We are all well acquainted with the fact that specific types of ceramics have a general and indisputable dating value. In such cases only the youngest object is significant, quantities play a minor role. From this angle, the most informative record for ceramic study, were for me, those from several excavations of a single stratum within the walls of Emona, a stratum which is almost always present and is the deepest archaeological layer, cut by the foundations of the first built structures and covered by the oldest mortar pavement. Fragments of Iron Age pottery can also be found here. However, the majority of the fragments originate from the Augustan period; several individual fragments are reliably made of sigillata dated to the late Augustan period and during the first years of Tiberius's reign (Mikl Curk 1973, 1977). It is thus evident that the formation of this stratum ceased at the moment when house construction inside the walled and planned town area was completed.

However, quantification plays a very important role in dating an individual unit where the ceramics (as well as other materials, of course) have a relative chronological value. At this point it is of key importance how the features of any particular period within a complex obtain their dating value, or to what extent those features are disappearing. As an example, let me present some of my observations regarding coarse Roman pottery, partially hand-moulded or moulded on the slow potter's wheel. This kind of pottery is somehow "softer" to the touch, inclusions are often limestone, grains have rounded edges, so that it appears as if the clay had been carelessly kneaded. But quite a lot of coarse pottery made on the fast wheel has been found as well. This type represents the second group of coarse kitchen pottery in Slovenia. It is usually very "hard" to the touch, so well fired that it gives a distinct sound, inclusions are often finely ground, sharp, small grains of flint. The most frequent coarse pottery form is the oval pot, although there exist a number of other objects made of such a ware. The place of manufacture can only rarely be identified, but the majority of these objects are presumed to be of local origin, although we are aware that this pottery was sometimes sold far away from the place of its manufacture. It is most difficult to ascertain how many vessels we are dealing with in an individual context from the recovered fragments of pottery. The possibility of error is greatest in these cases. Undoubtedly, the huge difference in manufacturing techniques cannot be attributed only to chronological causes. The most primitive and the most accomplished types appear side by side in the same situation and in the same closed context. Each individual technique produced vessels suitable for specific purposes –vessels with walls porous enough for food storage, vessels resistant to open fires, etc. Mould details with a wavy line on the surface appear throughout the entire Roman period and at various sites throughout the country. But particular features are not present at all locations or in equal frequencies or equally represented at all periods. It is therefore important to determine which particular features on the ceramics prevail within an individual archaeological group. Accordingly, I presume we could consider, for instance, unevenly kneaded pottery, decoration with a belt of wavy horizontal lines drawn by a comb, as characteristic of some specific environment and of a specific period (near, but not as exactly defined as in Rodrigez 1977, 1992), or for large pots with a surface that gives an impression of being impregnated by wax, as the characteristic of central Slovenia from the same time or even from the Migration Period – the Dark Ages (Mikl Curk 1975, 1992a). Or furthermore, the oval, roughly shaped pots of the early Middle Ages, often defined by an irregular texture and decorated with lines and prints, all of which testify to the use of a more robust potter's tools. However, I must point out, that one individual fragment of a specific kind of pot, is never enough to play a decisive role in determining the archaeological record. The most important statement in the record is: in what percentage is the described feature represented. Due to the modest numbers of finds in the later strata of Slovenia, a single fragment can represent up to 10 % of the total!

The frequency of individual types of ceramics of known origin, provides a snapshot of the *intensity of trading* and indirectly of all kinds of *other connections*. A number of researchers are engaged in studying this topic both in our country and abroad, so that the working method is well known as is the probability of error. An achievement of the study of ceramics in Slovenia is the study of WHY only particular kinds of terra sigillata are represented in specific archaeological groups, while many of other contemporary products cannot be found. The assumption that the volumes of material transported by sigillata merchants was often quite large (several sets of services) and that therefore the merchants delivered only the sigillata from a single or at least from one smaller group of manufacturers to one place at any one time, has not yet been disputed (Mikl Curk 1987, 1992).

The frequency of finds of vessels, sorted by function, enables us to draw conclusions concerning the activities that took place within specific buildings, *a conclusion about the purpose of a specific building*. Of course these conclusions demand special attention. Stratigraphic data is especially important. All the tools and vessels which had been used in a building do not necessarily remain there after any change, even where a pavement has been left intact. To illustrate: numerous remains of former drinking vessels were left all over the first century AD paved floors of small rooms in the forum of Emona. It is quite probably evidence of the sale and consumption of all kinds of liquids. But at one end the earthen joints used as support for vessels when placed in kilns were also found among the fragments. This testifies that empty vessels were sold as well. The irony is that the early nineteenth century gardens owned by a Ljubljana faïence manufacturer were located at the same site where the Emona forum once stood. For some inexplicable reason the ashes and other remains from the kilns of this faïence factory, which was documented at the other side of the town, ended up there. Ceramic plugs similar to the Roman ones (although not identical in colour and texture) and which were used in kilns as a support for pots were mixed with the top, humus layer, over these remains! On the other hand, practically no finds were discovered in the sandy strata of the forum plateau. Similarly, only a few pot fragments were found in the stratigraphy of the large forum buildings, which L. Plesničar Gec believes to have been built in the third century. This is understandable. The walls and stone paving of these buildings were still partly preserved at the excavation site. In a regulated settlement daily waste, whatever this might have been, was usually removed from site. Moreover, this data in a way supports the presumption that activities in which pottery was used did not take place in the town basilica. Large impregnated pots were found in the stratum covered by these remains (outside the buildings); a discovery which leads me to suggest that this kind of pottery belongs to the period when larger constructions were still standing but were no longer serving their original function. After all, we could hardly imagine that in a regulated town organism the most common food was being prepared and stored or that various common and everyday activities took place close to the external walls of the court basilica or the church portico. The dating of similar ceramics from the late Roman settlement at Vranje in the late fifth century (Knific 1979) confirmed this presumption.

For some other kinds of ceramics dated to the same period and originating from contemporary as well as earlier layers it can sometimes be concluded, that even after changes to the buildings within the constructed area of Poetovio, the ceramics remained close to the location where they originally served their purpose. We thus proposed, on the basis of two distinct locations within the area of Roman Poetovio, an undoubtedly bold and as yet unconfirmed assumption, that the middle Gallic sigillata had been reserved for the upper, mainly officer class of the town, while Rheinzabern pottery was available to the common inhabitant (Mikl Curk 1990).

3. The use of arable land

In our country there are only five, or perhaps six, extensive plains on which were situated all the Roman towns or major settlements. The Vipava valley (Vipavska dolina) which widens in the hinterland of today's Ajdovščina – Roman Castra. The Sava alluvium which stretches beneath the southern foothills of Karavanke Alps from the Sora plain (Sorško polje) to the higher regions of the Sava plain (Savsko polje) north of Ljubljana in the direction of Kamnik. These plains are the wider hinterland of the town of Kranj – the late Roman Carnium, but in the distant past they were mainly the hinterland of Ljubljana – Roman Emona. The Savinja valley (Savinjska dolina) is dominated by the town of Celje – Roman Celeia, the Krško plain (Krško polje) was in Roman times dominated by Drnovo near Krško, now an insignificant settlement, but in those times Neviodunum. The Drava and Ptuj plains (Dravsko and Ptujsko polje) were in Roman times certainly exploited by today's Ptuj – Roman Poetovio. The smaller plain around Slovenj Gradec belonged to the territory of the Roman Colatio, then located at Stari trg near Slovenj Gradec. These plains differ slightly, with respect to the pedological and partly hydrological characteristics, so that reliable conclusions about the extent of cultivation in Roman times cannot be made. Due to the consistent cultivation of these plains, any remains of actual Roman fields are not recognisable even on aerial photos. It is also unknown to what extent the Romans were interested in their agrarian potential. It certainly wasn't their primary interest. Above all, the territory of Slovenia attracted them for its strategic and communication potential, and to a certain degree as a source for material wealth. The existing roads which have been in use for a long time, and the cadastral border-lines, in some places indicate the shape of fields which might have been formed in Roman times (Mikl Curk 1984); yet all these facts are still far from being confirmed. However, we do have a fair knowledge of the traces of settlements and roads constructed during the Roman period on all the above mentioned territories (Mikl Curk 1993a). These traces do not inform us of the cultivated areas, but the plains are measurable and this information can be used for basic calculations. Poetovio was a military camp throughout the whole first century AD. The fact that a legion needed at least 600 tons of corn or equivalent quantity of other crops to pass the winter months, plus a less well known quantity of supplementary foodstuffs. In the eighteenth century in these regions, approximately 150 – 175 hectares of fields would be required to provide such a quantity of corn. For the Ancient World we have to approximate the minimum harvest per hectare. From this we can conclude that a legion could have needed as much as 10 – 15 % of all cultivable land within the reach of the town (Mikl Curk 1993). Of course, we have no knowledge of how many of these areas were already cultivated before the Romans came to the area, nor whether the legion actually supplied itself from the products produced in the surroundings of castra hiberna. Perhaps it might soon be possible to complete and extend this entirely hypothetical study.

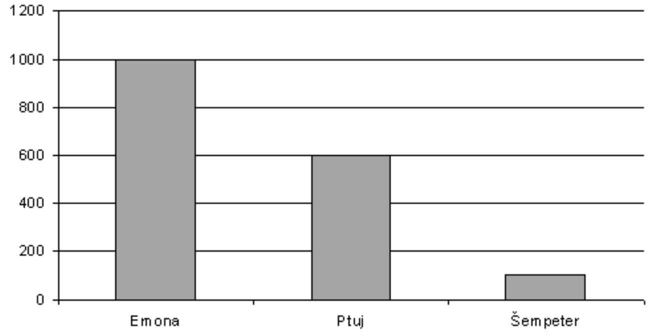

Figure 1: The number of analysed graves.

4. The cemeteries

Funeral gifts and aretefacts placed in tombs are in each civilisation characterised by numerous, specific and complicated symbology. In a prosaic sense, they signify the result of an instantaneous occurrence. In almost every cemetery individual tombs differ, although they have common features. The possibility to document varieties and similarities is obvious, as also is the wish to understand their causes. Regarding research on the Roman period in Slovenia (figure 1), the possibilities for such analysis became a reality after the comprehensive studies of the Emona cemeteries were published and after recent research of a large part of these cemeteries (Petru (1972) published the old data and Plesničar Gec (1972) the recent excavations). The first analyses of these and later cemetery data have certainly condensed the chronological aspect and at the same time revealed the popularity of specific methods of burial, with objects in the tombs characterising the deceased by sex (figure 2). Such synoptic tables have already been included in the publications of Emona material. Chronological and typological questions were treated by Plesničar Gec 1977, and several other authors in Arheološki Vestnik 30, 1979. The criteria for determining the sex from "male" and "female" jewellery, parts of clothes, knifes, mirrors, phials of scents, small chests, needles and similar, are still unreliable; although the results obtained so far are quite good for cremation graves. Experiments with selection of objects and their origin from a specific civilisation (the origin of the type and not the individual product, whether from a Mediterranean or from a local tradition) gave identifiable results concerning the, simplified, ethnical and social affiliation of the deceased (Plesničar Gec 1985, Mikl Curk 1985, 1996). These results are not numerically insignificant. Throughout this work we were aware, and would remain so, that at the starting-point of such studies one meets a range of unexplained facts. It should therefore be taken into consideration that the clear relationships of each human community with the objects it uses in a specific superior or symbolic function (as their funeral use is) are possible only as long as the community can be clearly distinguished from the other communities with which it lives; e.g., for as long as the Italic colonists could be clearly distinguished from the natives, during the first period following Roman occupation. In the next generations these traces would already have lessened.

A fair number of similar problems still wait their turn to be closely studied, and the investigation of those is our future task.

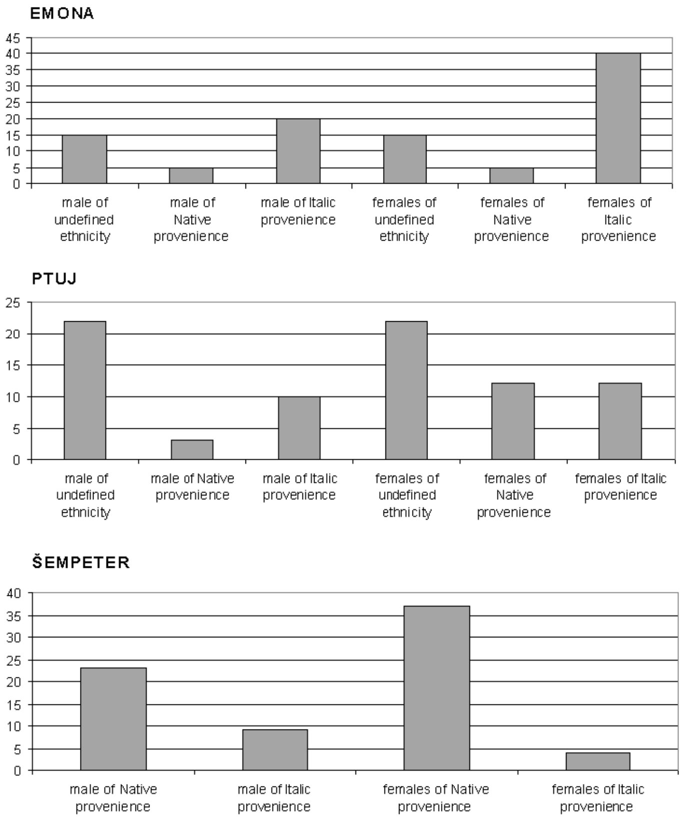

Figure 2: The number of graves, from the same sites, possibly defined by the sex of the deceased but separated upon the groups of men of undefined ethnicity, men of so-called Native and men of Italic provenience, and groups of women of undefined ethnicity, women of the so-called Native and women of Italic provenience.

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Image Quantification as Archaeological Description

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Abstract

This paper deals with the use of microscopic images as a way to define textures, and with the statistical analysis of quantitatively described textures. Digital image processing is a normal technique in archaeology. Archaeological images range from the microscopic to the macroscopic, and a diverse toolbox of computer techniques is available to process such archaeological data. However, the very nature of images as archaeological data has not been evaluated. Images are not primary data, but a transformation of empirical reality, translated into a language of luminance contrasts. Images are therefore the result of a goal-oriented modification. But how may this modification alter the reliability of the analysis? Very few studies have been published as regards this topic. Our goal in this paper is to integrate different archaeological applications of microscopy (use-wear in lithic tools, and pottery archaeometry) in order to define the observational category we are dealing with: texture. If the texture is the complex set of surface properties in an artefact, how can we describe it? What kind of archaeological, historical information do we obtain from the analysis of texture? A related problem is that of image sampling. Digital image techniques have been applied in disciplines where the assumption of surface homogeneity is valid. However, the modified surface of an archaeological artefact is always discontinuous. Different images can be obtained from the same artefact, and all of these images may be different. Statistical sampling is therefore a basic problem in archaeological image processing, and very few studies have been made. We explore the use of neural networks and related approaches to deal with this problem.

Key words: image processing, use-wear, archeometry, lithic analysis, pottery analysis, microscopy, neural networks

1. The concept of texture

Work modifies matter. As a result of human action, matter is exposed to changes and modifications, the result of which we call *artefacts*. David Clarke defined an *artefact* as anything modified as a result of human action: a tool is an artefact, in the same sense as a house, a pit, a burnt bone or a landscape (Clarke 1978). Social Sciences study how humans modify nature by creating artefacts, and these artefacts should be described in terms of human induced modifications on natural resources, and the sequence of changes across time.

Consider a lithic tool. It is made of stone, consequently, we should explain its *cause* as a human modification on a natural resource (flint), producing as an *effect* a *product*, an artefact whose properties are the result of the modification process or *production*. The same idea is valid for a vase. Here production can be described as: obtaining the resource (clay), obtaining other resources (temper, water, fuel), and processing them. In both cases, artefacts should be considered as nature modified by humans.

The goal of Archaeology (or one of its goals) should be the analysis of these processes, that is to say, the study of how humans modify natural resources in some specific historic circumstance. We study a *cause-effect* relationship, i.e. how social activity *causes* observable modifications in nature. Therefore, we should process a set of observable properties in order to be able to identify material effects of human work. Although the list can be very long, we consider that observable variability can be reduced to: shape, size, composition, texture and location.

Shape and size are the most commonly analysed properties of artefacts (see, for a theoretical introduction Small 1996), as it also holds true for location analysis. There is a lot of research on how to calculate the shape, size and location of lithic tools, pottery artefacts, metallic elements, etc. The shape of bones (human and animal), for instance, has been studied intensively in order to obtain taxonomic information. Composition is also a rather standard domain, especially in recent years: archaeologists are able to decompose any artefact into its compositional elements, both at a formal level (a house is composed of walls, a wall is composed of bricks), or on a physical-chemical level (archaeometry). But not many studies were performed on how human work modifies the surface properties of artefacts.

Artefacts have surface properties because of the way they have been made, or the way they have been used. In this paper, we analyse *archaeological textures*, that is surface properties, in pottery and lithic artefacts. In the first case, texture is a result of manufacture: different ways of producing and using a vase give a thin-section with a characteristic texture. In the second case, use changes the physical characteristics of the flint surface, producing a distinctive texture wear for each use. We explain how texture can be defined using different attributes, such as coarseness, contrast, directionality, line-likeness, regularity and roughness.

2. Observing textures: the creation of images

Observation is a process by which the human brain transforms light intensities into “visual” models. What we usually call *data* are not primary inputs, but a transformation of sensory information into an explanatory model of it. Observation is a 3 stage process: Perception, Recognition, Description (Bunge 1981, Hacking 1983), in which “perception” is only the first. Only once our brain recognises sensory information according to prior experience, we begin “seeing” reality around us. *Data* is the result of the final stage: description – that is, translation of recognised sensory inputs into a specific language.

Observation is a mode of knowledge acquisition, and it is used as a test mechanism for evaluating the reliability of already acquired knowledge. That is, observation is always an intentional act, guided by specific goals. As an intentional act, observation, even the so called "scientific" observation is always affected by available knowledge and can be direct or indirect, precise or wrong, misguided or even fraudulent. This fact leads some authors to reject the scientific method because without "objective" observation, there is no "objective" knowledge. However, given that observation is an "intentional" act, we can build observation in order to be objective. To do that we need is that observation results (data) be made public or collective, and not limited to a single observer.

"Objective" observation is produced by externalising perception, and by formalising recognition and description. We should impose control on:

- the object of observation,
- the observer and his/her/its perceptions,
- the circumstances of observation,
- the means of observation (senses, auxiliary instruments and procedures),
- a knowledge base relating to all above elements.

The means of observation, together with the related knowledge base are *the instruments of observation*. When we "externalise" observation in order to produce objective knowledge of the world, we mechanise the perceptual phase. That is we substitute human senses with a microscope, for instance. Nevertheless, this is not really a substitution. Instruments are necessary for perception, but not sufficient for observation, because nothing can be detected without an observer. The world is not data, but a set of perceptual information waiting for an observer to impose order by recognising an object and by describing it. What we are doing when we use the microscope is trying to avoid perceptual misinformation: a microscope allows two different observers to agree on the perceptual basis of information, but they can disagree on the recognised objects and how to describe the recognised world. Therefore, a fact can be observed if an agent *a* (the observer) is able to record some perceptual information *p* using an instrument *r*, under some circumstances *y*. The instrument is as important as the circumstances of observation, which includes the goals - the knowledge to be tested.

Images are not something to be captured, because they are not a part of reality. They are data, that is formal descriptions of something that exists. Light and colour are properties that really exist in the world, and they can be captured using special devices which transform light into electric or chemical signals, which should be manipulated in order to create a representation (an image).

Data, which is the result of the observational process, is only a model, a representation of some aspect of reality. Given that images are a kind of data, they are not a manipulation of reality, but a guided and intentional explanatory representation of some regularities existing in that real world. They are "real" only in the sense that they are true, that is, they coincide with the real world. Consequently, shape, size, texture, etc. are properties of a perceptual model of reality. Any "visual model" is only a spatial pattern of luminance contrasts that explains how the light is reflected, and it is composed of visual bindings which can be divided into sets of marks (points, lines, areas, volumes) that express position or shape, and retinal properties (colour, shadow, texture) that enhance the marks and may also carry additional information (Foley and Ribarsky 1994, Astheimer et al. 1994). Points and areas connected by the same plane or surface have not the same values. This variation is called *texture*, and it is used to understand those geometric properties that are based on local features. Each surface appearance should depend on the types of light sources illuminating it, its physical properties, and its position and orientation with respect to the light sources, viewer and other surfaces.

A microscope is not a device producing data, but it is used as a perceptual mechanism, whose output is the input of our model. A picture is not primary data, but a visual model of some real world properties, among them also *texture*. Thus (see Marr 1982, Watt 1988, Gershon 1994, Wadnell 1995, Barceló 2000):

- a pattern of changes in light wavelength and surface-reflectance, should be translated into a model of *colour,*
- a pattern of changes in edge orientation (Curvature), where an edge is an abrupt change on luminance values, should be translated into a model of *shape*,
- a pattern of changes in luminance variations in a scene with non uniform reflectance, should be translated into a model of *texture*,
- a pattern of discrimination between edges at different spatial positions, should be translated into a model of *topology,*
- a pattern of discrimination between edges at different spatial-temporal positions should be translated into a model of *motion.*

Although humans readily recognise a wide variety of textures, they often have difficulty describing the exact features that they use in the recognition and description processes. In this paper, our goal is to explain how to create a visual model of texture, using geometry as the formal language for recognition and description of microscopic visual inputs.

3. Describing texture: measuring images

An image is not a surrogate for reality, it is a directed and intentional transformation of reality in order to extract some relevant information. The microscope is not a device for observing some aspect of reality, but for capturing some initial input (luminance perception), which should be translated into observed data by a human agent using a visual model. What we are looking for in that image is the patterning of luminance values across all pixels. This is not the texture of the image, but we should *recognise* texture patterns in it, and build a geometric model of it. This can only be done with the help of prior knowledge as regards the concept to be modelled. The way of obtaining that knowledge is relatively simple: by comparing different images observed in experimental conditions.

Our main assumption is that different artefacts have different textures because they have been altered by different work activities. Consequently, the geometrical model of luminance patterning in each microscopic image should be different, if the activity performed by that artefact was different. We should create a *prototype* model of texture produced by a specific activity, quantifying also different sources of variability within that model, and maximising the variability between models for different activities.

The texture of different images should allow us to discriminate between image groups with some characteristic pattern of luminance variation. Nevertheless, the problem of luminance pattern variation is a complex one. When we see a picture, we *recognise* some differential features (striations, polished areas, scars, particles, undifferentiated background). These features are then a consequence of our prior knowledge, although in some way, they exist in the image. *Recognition* is a subjective procedure if we follow our individual criteria. However, this stage can be formalised, using an algorithmic approach: if we can reduce the amount of irrelevant variation in luminance patterns, the result is a formal representation of relevant features. Of course, what is relevant or irrelevant must be strictly defined. That is, we should distinguish two kinds of texture, one of them is inherent to the artefact surface, and the other one is the result of modifications on the surface generated by work activities. Furthermore, we should also distinguish luminance variations produced during the perceptual stage as a consequence of microscope functioning. Given that generated texture modifies inherent texture, a formal procedure of deleting random variation should allow the extraction of "dominant" or relevant features. We should not look for "meaningful" features, but we should describe formally (quantify) relevant variation measured in a experimentally controlled situation in order to define variation patterns regularly associated with each experiment.

Once relevant features have been extracted ("recognised"), the construction of a geometrical model of their relationships is a fairly straightforward task.

Consequently, analysing archaeological textures is not a single comparison of images, but a comparison of geometric models. Each model is a generalisation of surface properties "observed" through a microscope.

3.1. Quantifying texture

We should take into account that properties of any visual model are expressed as intensity values of colour variation, light and reflectance over surface (Sonka et al. 1994, Ebert et al. 1994). Therefore, a digital image of texture properties is a two dimensional mapping of points (p_i, q_i) with a specific luminance value (r_i). The resulting function is then $p_x q_x r$.

Texture is then described as the relationships of luminance values in one pixel with luminance values in neighbouring pixels. These values can be modelled as forming a set of regions, consisting of many small sub-regions, each with a rather uniform set of luminance values. In our case, these values are defined as grey levels. A group of related pixels can be considered as a texture minimal unit, sometimes called *texel* - texture element - (Sonka et al. 1994). Texture patterning in an image should be described as associations between *texels*.

A two-dimensional measure of texture is based on co-occurrence matrices, which show how often each grey level or luminance value occurs at a pixel located at a fixed geometric position relative to another pixel. For instance, an (3. 17) entry in a co-occurrence matrix means the frequency (or probability) of finding grey level 17 immediately to the right of a pixel with grey level 3. Each entry in a co-occurrence matrix could be used directly as a feature for classifying the texture of the region that produced it. Each different relative position between the two pixels to be compared creates a different co-occurrence matrix (Gose et al. 1996).

The first task in texture description is the *segmentation* of zones with the maximum contrast of luminance (texels). This task can be approached by calculating the *texture gradient* in the image - that is, the direction of maximum rate of change of the perceived size of the texture elements, and a *scalar measurement of this rate* (Sonka et al. 1994). This texture gradient describes the modification of the density and the size of texture elements and so regularity patterns in luminance variation can be determined. A *convolution filter* can be designed so that each pixel in the original image is transformed according to the following function:

$$g(x,y) = \mathrm{G}\left[\, f\,(x,y)\right] = \left|\frac{\delta f/\delta x}{\delta f/\delta y}\right|$$

that is to say, each pixel (with *x*, *y* co-ordinates) is transformed according to the median of the derivative of its pixel neighbours. This is called a *gradient operator.* Its magnitude is defined by the following expression:

$$mag\left[\mathrm{G}\left[\, f\,(x,y)\right]\right] = \left[(\delta f/\delta x)^2 + (\delta f/\delta y)^2\right]$$

This operator increases luminance values in areas with sharp luminance and brightness contrasts, and decreases the values in areas with soft luminance and brightness contrasts. As a result, isolated areas are segmented whose shape, size, texture, composition and position may be measured (Pijoan et al. 1999).

3.2. Real image, segmented image and "texel map"

Once texels have been extracted, we should calculate their formal and relational properties, using their variables of shape, size, composition, texture and position. Among others we should measure:

- Area measurements (number of pixels *within* a texel).
- Perimeter measurements (number of pixels around the edge of a texel).
- Perimeter shape. Measured as a pattern of changes in edge orientation.
- Convex Hull: the smallest region which contains the texel, such that any two points of the region can be connected by a straight line.
- Euler-Poincaré characteristic: difference between the number of regions (texels) and the number of holes within them.
- The Frequency and Entropy of Brightness within a texel (histogram of grey levels).
- The Frequency and Entropy of Contrast: local change in brightness (ratio between average brightness within the texel and the background brightness – neighbouring texels).
- Topology of Texture. A pattern of discrimination between the edges at different spatial positions, distance and adjacency relationships between different texels. Among them:

  Degree of Coarseness: edge density is a measure of coarseness. The finer the texture, the higher the number of edges are present in the image,

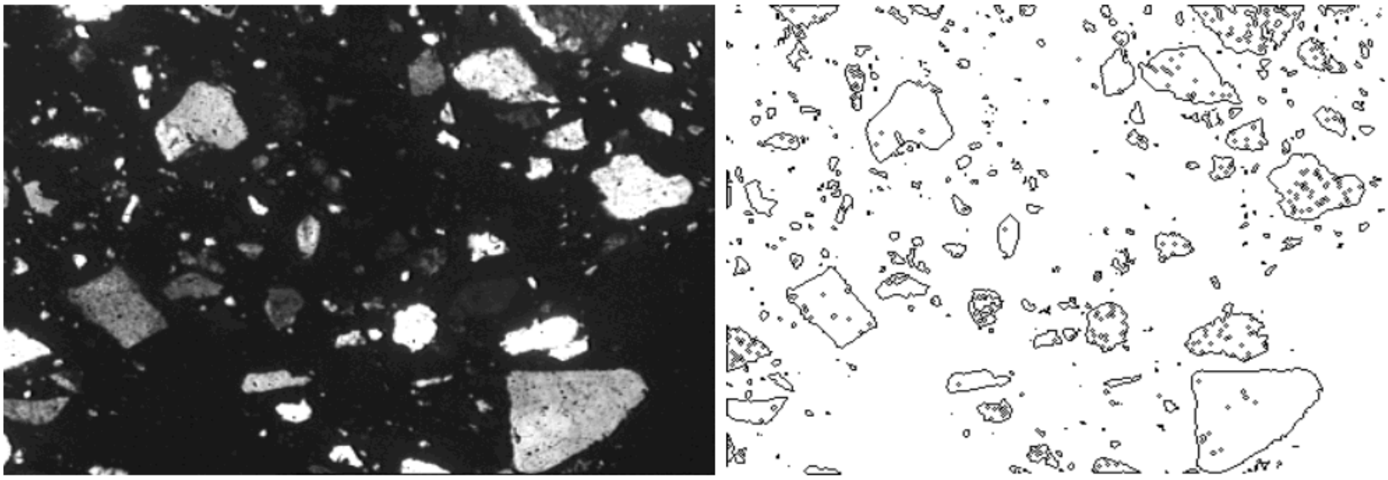


Figure 1: Describing mineral particles in a pottery thin-section by means of texel extraction.

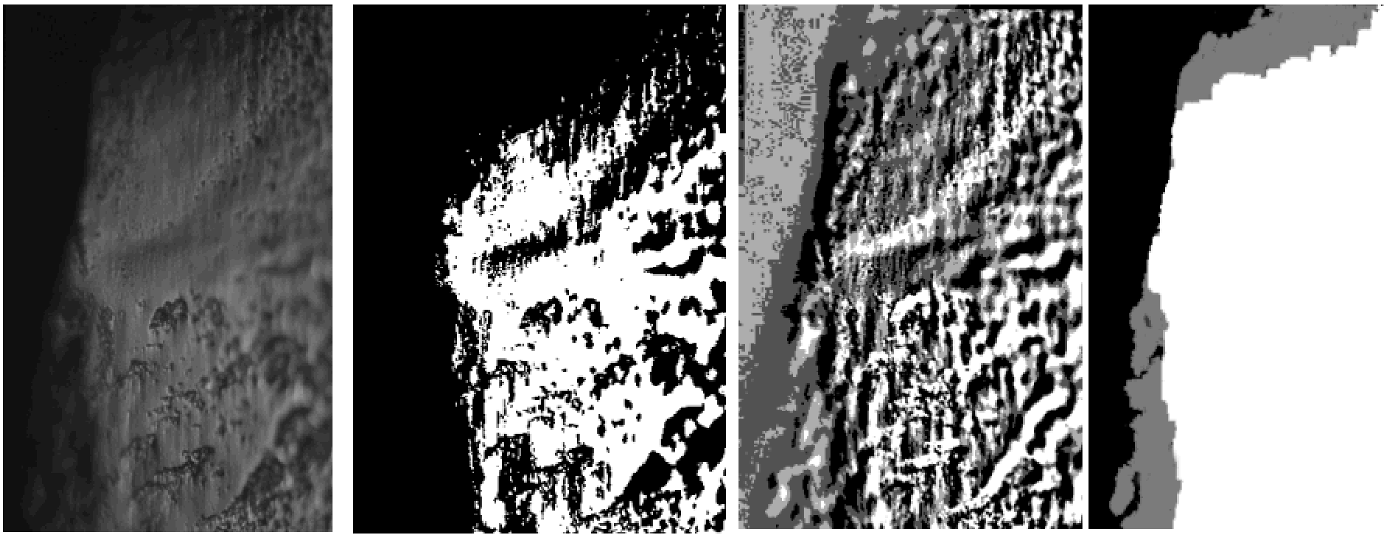


Figure 2: Extracting use-wear areas by means of texel extraction.

> Contrast: high contrast textures are characterised by large edge magnitudes,
>
> Randomness: may be measured as entropy of the edge magnitude histogram,
>
> Directivity: entropy of the edge-direction histogram. Directional textures have an even number of significant peaks, direction-less textures have a uniform edge-direction histogram,
>
> Linearity: is indicated by the co-occurrence of edge pairs with the same edge direction at constant distances,
>
> Periodicity: texture periodicity can be measured by co-occurrences of edge pairs of the same direction at constant distances in directions perpendicular to the edge direction,
>
> Size: texture size measures may be based on the co-occurrence of edge pairs with opposite edge-directions at a constant distance in a direction perpendicular to the edge directions.

In the long term, this approach should be directed to the generation or *synthesis* of texture from a program or model, rather than just a digitised or painted image (Musgrave 1994). We are looking for a “procedural” approach where the analysis of properties of observed textures is expressed as a statistical model which should be able to reproduce the textures from statistical data (Ebert et al. 1994).

3.3. Two case studies

The thin-section samples of pottery are utilised in petrography for the description of some petrographic attributes of the vessel fabric mineralogical composition. They are the results of a specific work process, where the productive agents modify the clay status of fabrics through a thermal alteration. These different petrographic attributes are the result of the natural formation of clays and the deliberated human alteration of them. We try to study thin-section samples in the most objective way. In this way we try to assign a series of numeric values to a thin-section microscopic image in order to quantitatively describe the sample. The purpose of this study is the description of mineral particles that compose the fabric of a vase. We represent each particle as texels defined against a general background (clay). In this way, mineral particles can be measured according to luminance intensity, shape, size, etc. The goal is to distinguish different vases (fabrics) from the different characteristics of particles contained in the fabric. These differences could be explained in terms of the manufacturing processes.

In lithic use-wear, we compare different images created as visual models of specific experiments. Each image is not a photograph of an artefact, but a model of the generated texture on a flint surface when an agent makes a longitudinal movement with that tool on a fresh wood material. Our goal is to distinguish between the visual model of that texture and the visual model of the generated texture on a flint surface when an agent makes a transversal movement with the same tool on a leather material. The extracted texels should be recognised as micropolish, microscarring and linear features. Each one should be considered a different kind of texel. We should distinguish these features produced by the movement of a lithic tool done on an specific matter, from the macro and microscopic traces characteristic of the lithic surface alone.

We have reduced the original complexity of microscopic images into grey scale pictures. In this way, it is easier to recognise texels. Once recognised, texels must be described. We use geometry to describe the shape, size, texture, composition and location of micropolished areas, scars and linear features detected on the lithic tool surface, or to describe the particles detected in the microscopic picture of a pottery vessel thin section. Shape is a property that can be used for the differentiation of texels, whereas size can also be used to differentiate between texels generated in different experimental conditions. Density measures give information about the texture (homogeneity within a particular texel) and the position. The following variables are those that the use-wear and thin section analysis techniques have used to describe the differences between cases, and to discriminate those between different groups:

Area measurements: The total number of pixels with the same luminance or range of luminance. The edge is defined by the proximity of a grey level. Normally a simple threshold operation is enough to define the area or areas of a discrete texel. In use-wear analysis we utilise the area measurements to extract the extension of micropolish, the size of microscars_and the striations length. Pottery thin-section analysis is used for measuring the size of each mineral particle in the fabric.

Texels perimeter: We took the information as regards the size of a mineral particle or the length of the striation. This variable is used for calculating different ratios of the variables related with the perimeter shape.

The *Euler-Poincaré* characteristic is used for measuring the ratio in the microtopography and the micropolish spread. This variable is not necessary in the thin-section analysis.

The *frequency* and *entropy of brightness* within a texel is calculated using the histogram of grey levels.

The *frequency and entropy of contrast*: local change in brightness (ratio between average brightness within the texel and the neighbouring texels) is used as an intermediate calculus to describe coarseness.

Perimeter shape and *orientation*: To introduce the category of shape we use the natural geometric shapes as indicators, in order to define the pattern of the geometric model of the sample.

Circularity: the degree of circularity of a texel. I.e. how similar is this texel to a circle. Where 1 is a perfect circle and 0.492 is an isosceles triangle. This shape is expressed by:

$$\frac{4\pi s}{p^2}$$

s: texel area
p: texel perimeter

Quadrature: the degree of quadrature of a texel, where 1 is a square and 0.800 an isosceles triangle. This shape is expressed by:

$$\frac{p}{4\sqrt{s}}$$

Irregularity: measurement of the irregularity of a texel, calculated as the relationship between its perimeter and the perimeter of the surrounding circle. The minimum irregularity is a circle, corresponding to the value 1. A square is the maximum irregularity with a value of 1.402. This shape is expressed by:

$$\frac{p_c}{p}$$

Elongation: the degree of ellipticity of a texel. A circle and a square are the less elliptic shapes. This shape is expressed by:

$$\frac{D}{d}$$

D: maximum diameter within a texel
d: minimum diameter perpendicular at D

All shape measurements are used in use-wear and thin-section for the study of tendencies in the geometric pattern, both for describing the orientation and shapes of the micropolish and the striations in the use-wear analysis, and mineral particles in thin-section pottery analysis.

Orientation: the orientation given by the angle of the detected linear features with the tool's edge is used in use-wear analysis to define the direction of the movement *made* with the tool.

Topology of texture: these measures are measured from relationships and associations between texels (and not at each texel).

Randomness: entropy of the number of texels within a modified surface. It can be used in use-wear for distinguishing the area of the micropolish from the background.

Linearity: linear features can be represented using linear equations: $y = a + bx$, where *y* and *x* are co-ordinates, and *a* and *b* linear coefficients. We use both coefficients as quantitative variables in our study. We can also include some other numerical attributes such as the quantity of lines, and their longitude. The width of linear features can be measured on a three-dimensional representation, and included in the image quantification.

Directivity: entropy of the edge-direction histogram. Directional textures have an even number of significant peaks, direction-less textures have a uniform edge-direction histogram. This can be used in the description of striation orientation.

Size: number of pixels corresponding to each contour in the image. It allows the study of micropolish topography.

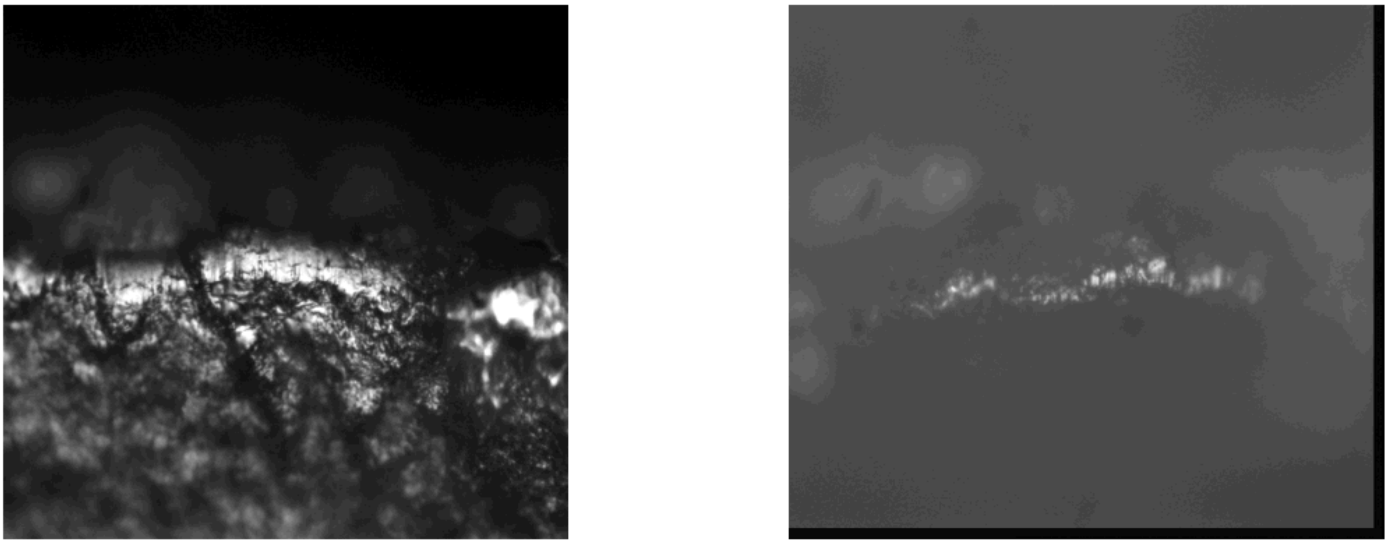
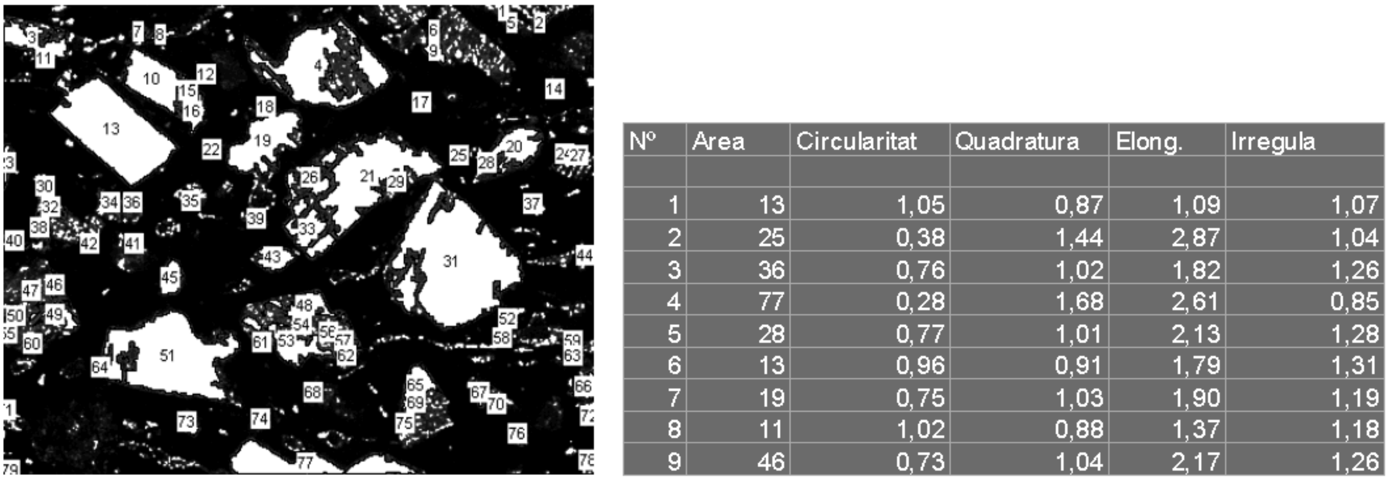


Figure 3: Variations in texture due to focus adjustment. Only the edge of the tool is visible.



Nº	Area	Circularitat	Quadratura	Elong.	Irregula
1	13	1,05	0,87	1,09	1,07
2	25	0,38	1,44	2,87	1,04
3	36	0,76	1,02	1,82	1,26
4	77	0,28	1,68	2,61	0,85
5	28	0,77	1,01	2,13	1,28
6	13	0,96	0,91	1,79	1,31
7	19	0,75	1,03	1,90	1,19
8	11	1,02	0,88	1,37	1,18
9	46	0,73	1,04	2,17	1,26

Figure 4: Measuring texels.

4. The variability of textures: statistical sampling

A single microscopic image is not a good prototype to determine the artefact's texture properties. This assumption would be correct if all the artefact surfaces were modified in exactly the same way. In the case of use-wear in lithic tools this is clearly not the case, because modified texture related to the work activity appears only in some areas of the surface. Consequently, a geometric model of textures cannot be built as a generalisation of a single image. Sources of variability are too important, and should be taken into account.

Measurement error is the most obvious source of variability. Features we "observe" in a microscope image come from a 3D reality, but the picture is a 2D model. As a result, any image should be considered as a modification of perceptual reality, because it cannot maintain the same focus for the entire field of vision. It is impossible to give the same sharpness to the complete observed surface, because it is not on the same level. As a result, microscopic images are characterised by narrow observation plans, that can be wrongly considered as discrete texels. This is a case of measurement error, and the only way to deal with it is by not using primary images, but modified visual data. That is, texture data should be composite images made of microscope pictures taken with different focus levels. By merging all levels into one, and by posterising them, we obtain a visual model of a sharp-equalised image.

Colour and shadow are also some sources of measurement error. They are the consequence of light reflection across the artefact's surface, and, in a reflected light microscope – used in material sciences – this reflection depends on the angle between the light beam and the observed layer. In these circumstances, we can get a paradoxical situation where a polished texel (more light reflection) seems darker than an unpolished texel, which is less reflective, but light reflects at a perpendicular angle in respect to the source of light. Observing coarse areas (texels with a large number of minor variations of luminance contrasts) is then a matter of light orientation, and not only of surface parameters. To appreciate this, it is only necessary to consider a regularly patterned object viewed in 3D - two effects would be apparent; the angle at which the surface is seen would cause a perspective distortion of the texture element, and the relative size of those elements would vary according to the distance from the observer. The best way of dealing with this source of measurement error is by controlling all observation parameters, and maintaining all of them fixed during the entire procedure. Among these parameters, we can find the following: the distance from the observer slant, the angle at which the surface is sloping away from the viewer (the angle between the surface and the line of sight), and tilt, the direction in which the slant takes place (Sonka et al. 1994). The control of observation parameters is not an easy task, because there is not a single perceptual plan that is useful for all kind of observations. Some features are best seen with perpendicular beams of light, while other can be discovered only using fast horizontal beams.

These are some of the sources of error measurement, and there is a long tradition of dealing with them and reducing their effects. Less known are the sources of variation that prevent the simple generalisation of perceptual images. In our case, the main problem is that the microscope field of vision is too limited for our purposes (from a 4x4 cm. field in the easiest case, to 0.001x0.001 mm or less, if we use electronic microscopes). Without further investigation we cannot accept the assumption, that a reduced frame contains all the elements that characterise the complete surface. We need more than one single image to correctly represent all texture variation present in the surfaces of the artefact.

Consequently, sampling questions are of great importance. In this research we have used a series of images to investigate the variability of texture within an artefact, before using the resulting geometric model to explain differences between artefacts. The problem is to merge different files containing shape, size, composition, texture and position of individual texels identified in all images of different artefacts.

We have used the following approach:

4.1. *Within-artefact* description

We have considered the processing of all observed texels in different images of the same artefact. The number of images depends on the complexity of texture and the position of modified surface patterns. In our research we have selected three or four images for each artefact, in order to look for differences among all texels produced in the same experimental conditions in the same artefact. These texels are described using the variables defined above, and within-artefact variation is then analysed, using standard statistics.

The purpose is not only to describe variation, but also to define prototype values for relevant features. For instance, we have used mean and standard deviation of area and perimeter measures, as well as skewness and kurtosis measures. It is not the absolute value of these prototypes that interests us, but the range of variation each texel may adopt within an artefact.

4.2. *Between*-artefact description

Of course, central-tendency measures are relevant only if within-artefact variation is approximately normal, and this assumption should be tested in each case. However, even when within-artefact variability is not normal, measures of dispersion can be used to compare textures produced by different activities. In some cases, there is not any identifiable texture pattern associated with some specific activity, but a greater or lesser dispersion of values than others. For instance, micropolish in use-wear analysis should be understood not as a discrete texel, but as an area with a low degree of texture variation due to friction, and given as a result a specific luminance value due to light reflection on that homogeneous surface.

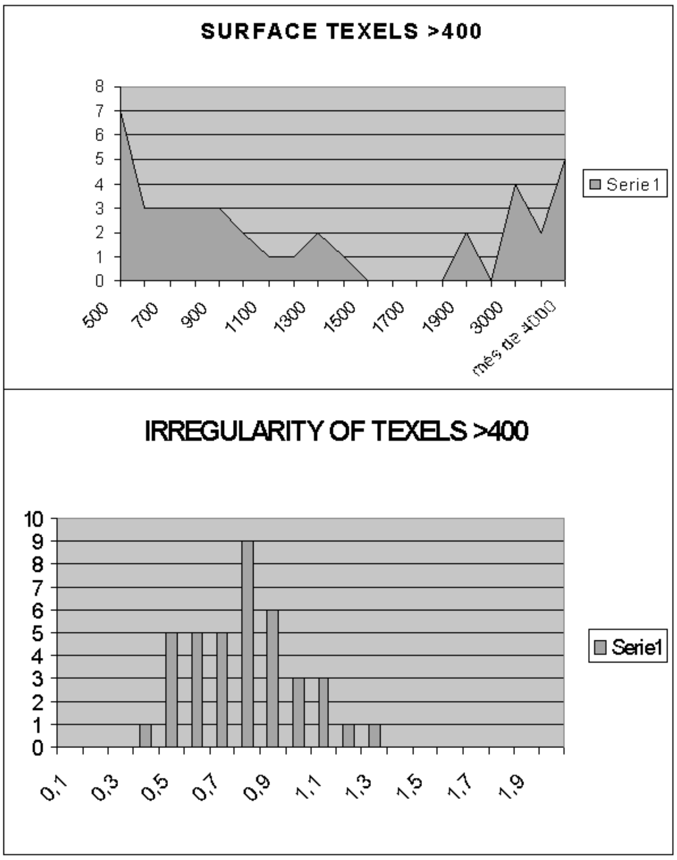


Figure 5: Statistical analysis of some properties (Surface, Irregularity) of the biggest particles (more than 400 pixels surface area) from all four microscopic pictures of the same object.

In such circumstances, specifically when normality is not assumed, between-artefact variability is very difficult to discriminate. In order to perform this task we have used a neural network approach (Barceló 1996, Barceló et al. 2000).

The system we want to build is a diagnosis machine that predicts the probability of any artefact (a lithic tool, a pottery vase) to be it used or produced in any way, given a set of inputs (a quantitative description of macro- and microscopic texels extracted from a number of different images of the same artefact). This prediction does not follow a rigid algorithm in producing an answer based on given inputs, but it is actually learned through training examples.

The network consists of many simple, but individual processing elements ("nodes") arranged in one or more layers and a system of connections. These connections transmit the signals, which the nodes manipulate. A transfer function contained in each node governs this manipulation. The nodes add weight adjusted inputs, and a bias value, and finally they pass the result through an activation function (also called a transfer or squashing function) to be used by other neurones or offered as an output. A learning process is usually performed in the network of connections. Although a network's transfer functions usually do not change, the connection strengths change during the learning process. These changes result from the network making predictions on training examples, which contain known outputs based on real inputs. In our case, training examples are pairs of archaeological experimentation results, that is, the descriptive features observed in those lithic tools that were used for some specific activity in the laboratory.

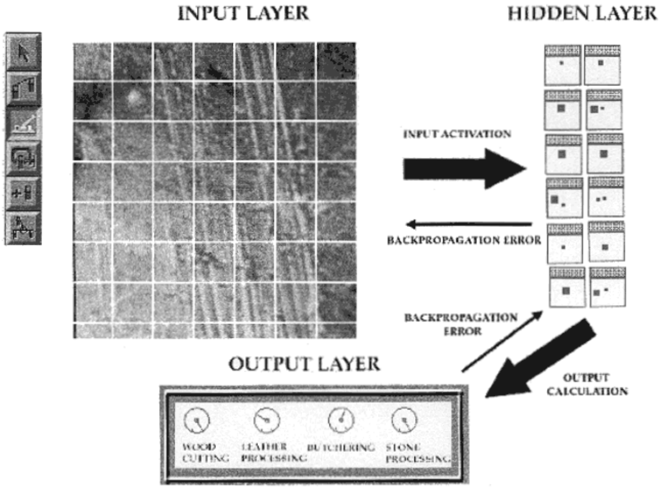


Figure 6: A Neural Network scheme for the analysis of use-wear microscopic pictures.

Observable information (image data) is the input to the first layer which then propagates through the structure of connections and nodes. When the input values finally reaches the output nodes in the final layer, these units produce an answer (a number reflecting the intensity of the function in each unit), which is the network's prediction of the output based on the given data input. The predicted output at every node in the final layer is then compared to the correct (known) output at every node. Errors are generated as the difference between the correct output and the network's predicted output. These errors propagate backwards through the network, modifying the connections' weights based on a mathematical equation that defines what is described as the learning rule. This process continues until the user is satisfied with the accuracy of the network's predictions.

Once the network is satisfactorily "trained", it is put into actual use. The network is fed only input data, preferably data it has never seen before. Feeding the network the exact same data that was used during training only tests the network's ability to "memorise" data. A useful network can accurately predict output to data it has never seen before.

The real challenge in developing a useful neural network system is the training process. We are comparing different supervised learning algorithms where the "training" of the network is an iterative process based on large numbers of data samples representing the traffic flow within a certain region. Using standard connection weights, the network computes a set of outputs, and compares this set of outputs with the input values by calculating a root mean square difference (or global error) and modifies the connection weights to displace the outputs toward the expected values. If the training is successful, the global error is reduced. In over-simplified terms, gradient descent works to optimise a system by minimising a given function. In the case of backpropagation, network error is minimised by optimising the weights values of the connections among nodes. The total network error is minimised by following the gradient (actually followed down towards a *minimum*, hence descent).

Since many indicators appear to be relevant at first glance, we should perform sensitivity analysis with respect to the different inputs. This involves noting the percent change in the output caused by a specific percent change in one of the inputs, keeping all the other inputs the same. But we have also included the possibility of non-linear interactions, that is, changes to two or more inputs in tandem can have a different effect from that of changes to one input alone. Redundancy has not been deleted, because it was one of the goals in our analysis, that is, to evaluate if classificatory results are affected by redundancy. We have carried out only a preliminary sensitivity analysis, in order to drop features that do not produce enough information.

5. Conclusions

The way neural networks process redundancy and irrelevant variation is the reason we have selected this approach. It is important to realise, however, that an erroneous understanding of image processing has confused the fuzzy nature of image descriptions, even at a quantitative level. We think that redundancy, error measurement and within-artefact variability exists at the level of perceptual input, that is, they are inside the images we want to compare. Any experimental approach is nothing more than a "supervised-learning" framework, where it is assumed that between-artefact variation is greater than within-artefact variation, and its patterning can be distinguished. Most image analysis in archaeology and other disciplines neglect the sources of within-artefact variability and error measurement. In this paper we have proposed an approach to deal with this problem.

Acknowledgements

The authors would like to thank Assumpció Vila, Xavier Clop and Ignacio Clemente, for initiating the project and for their continued support during its development. We also express our gratitude to the Center for Computer Vision at the Universitat Autònoma de Barcelona for all analysis carried out using their facilities. This research has been made possible thanks to Project DGICYT PB97-1161 from the Spanish Ministry of Education and Culture. J. Pijoan is a bursary of The Universitat Autònoma de Barcelona, and he thanks this institution for his Grant. J. Pijoan and O.Vicente also received a special bursary from CAA2000. We would also like to thank the Ljubljana organisers for attending the conference. We acknowledge all the aforementioned financial supports.

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The SHAPE Lab: New Technology and Software for Archaeologists

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Abstract

The SHAPE Lab was recently established (1999), with a grant from the United States National Science Foundation, by Brown University Departments of Engineering, Applied Mathematics, Computer Science and The Centre for Old World Archaeology and Art and Department of Anthropology. It is a significant interdisciplinary effort for scientific research with a direct application to important problems in the analysis of archaeological finds and artefacts. We present the concepts that will underlie a 3D shape language, and an interactive, mixed-initiative system, for the recovery of 3D free-form object and selected scene structure from one or more images and video. This work has impact by providing new practical tools. It also provides an effective testbed for 3D shape reconstruction and recognition, more descriptive local and global models for working with 3D shapes and performing free-form geometric modelling, and for extracting 3D geometry from one or more images and video, as well as associated computational complexity issues. As applied to the field of archaeology, this technology provides, specifically, new ways to analyse and reconstruct pottery, compare objects from different sites and reconstruct sculpture and architecture.

Key words: *Shape language, 3D free-form modelling, ridges and valleys for shape, implicit polynomial models, medial axes, skeletal graphs, 3D object reconstruction and analysis, Great Temple of Petra, archaeological recordings*

1. Introduction

The SHAPE[1] Lab was recently established for the synergistic study of three dimensional (3D) free-form in the disciplines of mathematics, computer graphics, computer vision and archaeology. It answers the needs that arise in the domain of archaeology, but which are also generic across a range of applications. Specifically, we are investigating the following:

1. 3D free-form modelling for surface and volume representation, via the design of a shape language.
2. Geometric information extraction from either: (i) passive optical systems, such as obtained via a single image, many images, or a video stream, (ii) active data-capture systems, such as laser camera systems or structured light systems, and (iii) a combination of data obtained via (i) and (ii) together with auxiliary data when available (e.g. floorplans, survey data).
3. Human/computer interaction (HCI) for facilitating the model building and geometric information extraction, as well as to provide an interactive virtual system for archaeo-

Figure 1: Typical fragments of head sculptures from Petra, to be analysed. These fragments have considerable detail although some parts are missing and the surface is badly eroded.

logical analysis with site features, topography, architecture artefacts and special finds.

4. Decision-directed machine estimation for automatic model choice and geometric information extraction, with an emphasis on the important archaeological problem of stitching together fragments constitutive of an original object, such as obtained from pottery sherds.

These research topics are to be explored through an integrated effort because, on the one hand, the archaeology applications drive the 3D modelling and 3D from images research, and, on the other hand, the research on 3D free-form provides archaeologists with tools to be able to conduct research hitherto impossible or impractical. In addition, in light of the fact that the three disciplines of mathematics, computer graphics and computer vision view 3D free-form in various perspectives, ranging from theoretical to practical, this project provides a unique opportunity to conduct the study in a comprehensive way. Finally, we benefit from the direct involvement of our team of archaeologists at the site of the Great Temple in Petra, Jordan (see an aerial view of the Great Temple in Vote et al. this volume, figure 1) where on-going excavations have been conducted for many years, and from which a large database of artefacts is currently being built (Joukowsky 1998).

1.1. Archaeological research problems

We focus here on the development of a generic technology for the recovery of 3D models which is investigated in the context of archaeology. Archaeologists are typically faced with a series of bottlenecks, including the following ones, which this research aims to alleviate.

1. Excavators want to be able to register the location of artefacts in situ in order to maintain an accurate archaeological excavation record (see section 2). Our proposed technology will allow archaeologists to use relatively inexpensive equipment to expedite excavations and maintain more comprehensive, accurate and accessible records of artefact *geometry* and find locations.
2. Currently artists assist in work on site by documenting the artefacts found and positing reconstructions of broken artefacts, thus leaving archaeologists out of the process with additional delays and much added cost. Our proposed technology allows the archaeologist to use shape models and computer graphics to document and interactively reconstruct artefacts.
3. A significant problem in archaeology is the inability to compare many artefacts stylistically, which requires substantial physical information (e.g., see figure 1). Relating one artefact to another, perhaps found in another site, is an integral part of discovering its role, age, responsible artisan or community, etc. The expression of artefacts in a *shape language* will advance possibilities for interactive or automatic quantitative and qualitative comparison.

We rely mainly on image analysis and photogrammetric methods in order to reconstruct and measure the 3D structure of objects. The use of a passive optical data acquisition technology, in contrast to active scanners, is of interest in order to:

- acquire data on-site at low cost, without imposing hard constraints on the size of objects or the ambient lighting, and without slowing down the excavation campaign;
- use existing image databases from previous excavation campaigns and from other sites.

However, we also make use of active data acquisition techniques, such as laser scanning, structured light and computerized tomography (CT, see figure 2) systems, in order to:

- provide “ground truth” measurements upon which we can gauge passive reconstruction techniques;
- rapidly acquire 3D data in order to conduct our other research objectives;
- maintain an expertise in using both types of systems, and keep track of their evolving differences.

The last point is emphasized by the fact that digital photogrammetry has yet to become automated, while laser camera remain relatively expensive, structured light systems have limited applications in the field (i.e., constrained lighting conditions and limited field of view), and tomography is not a portable technique. See also the work of Pollefeys et al. (2000) who advocate the use of both passive and active systems for different purposes in documenting archaeological sites.

1.2. Shape modelling research problems

Our premise is that the use of more powerful 3D shape representations than the classical points, straight lines, planes, triangles or splines, can lead to practical solutions for the preceding problems, and markedly improve speed, accuracy, and user convenience over most of what is presently possible. The 3D representations we propose to study are hybrid constructions made of *ridges*, *implicit polynomial surfaces* (IPS, i.e., algebraic surfaces) and *skeletal graphs*. They are studied for use individually and in concert, in order to understand their most effective synergy as new hybrid models and algorithms are developed.

Of course, the guiding principle in this work is discovering and understanding the fundamental issues in solving these complex problems in computationally fast, yet user-friendly ways. We seek to identify the most effective ways of handling and processing the huge amounts of data available in the acquired images and video streams, in particular, by identifying tradeoffs between accuracy and complexity. We emphasize that our program for the study of 3D free-form representations for shape:

1. Solves heretofore unsolved problems.
2. Improves speed and user convenience in handling complex problems.
3. Handles huge amounts of data in new and faster ways.

In the remaining of this paper we first describe, in section 2, the present day situation at our main site of excavation, at Petra. Then, in section 3, we give some early results in tackling the previously introduced research objectives. Finally, in section 4, we describe in some detail the basis for our shape language developed to tackle complex archaeological problems.

2. Archaeology at Petra

The Great Temple of Petra, Jordan, is a monolithic structure at the top of a three-levelled precinct measuring 35 meters east-west, and 42.5 meters in length. In unearthing a site such as this, archaeologists want to use the most exact technology to register objects they excavate, and reconstructive technology to help them envision what the building and the objects within looked like (Joukowsky 1980). Our proposed technology aims to help them do both.

The latest archaeological standard for gathering data about finds is to register each object as it is excavated with a costly laser transit station. This requires three people to digitally register the object with the survey equipment; one to shoot the point, another to hold the prism in order to register the location, and a third to label and bag the artefact. Even with this method there is no easy way to correlate the object with the survey. Some archaeologists register an object with one point, indicating the approximate centroid of an object; others take four or five points (or more) per object in an attempt to give additional information about the object's shape and orientation.

In a typical excavation, relevant finds need to be registered with the survey station in different locations at once and excavators wait for the surveyors to register their objects before they can proceed with digging. Furthermore, all of the information regarding the find spot must be retrieved in the field. After the survey station has registered the object, it must go through other phases of registration. All artefacts are hand measured, drawn by a site artist, photographed and then put into a database of objects. All these steps must be completed at or near the site because artefacts cannot be taken home. Archaeologists require the ability to digitally register an object's orientation, detailed shape and other physical characteristics quickly and either on site, or a posteriori, when the data acquisition method allows it.

Figure 2: Figure made from density measurements of a box of sherds. Densities within the box were imaged volumetrically using a Rhode Island Hospital CT scanner. Iso-density surfaces were then created and rendered using marching cubes (Mortensen and Barrett 1998), a computer graphics technique.

The database for the Great Temple excavation contains already more than 115 000 artefacts, recorded since 1993 (Joukowsky 1999). Unfortunately, the full potential of archaeological databases is rarely realized. Most archaeologists are not able to analyse the geometric characteristics of artefacts and their spatial relationships with other elements of the site (Crescioli and Niccolucci 1998).

Our methodology encapsulates all of the above recording steps in one process. For example, 3D objects can be registered in the field via photogrammetric means (Leymarie et al. 1996). Our proposed technology will also permit archaeologists to reconstruct of broken or eroded fragments. Once 3D information is gained about artefacts and architectural fragments while objects are being initially registered, it will be possible to better exploit reconstruction possibilities. A series of pot fragments (figure 2 and 6) can be interactively, and eventually automatically, reconstructed, eroded sculpture reconditioned to understand the original features and surface, a wall rebuilt without having to lift heavy fragments, and many elephant-head column capital trunks reconsolidated. In many cases, archaeological artefacts go uncited as historically significant because they cannot be interpreted and referenced with other like examples. Our proposed technology allows archaeologists to understand and reference objects within a historic framework and also permits visualization that has, in the past, been unavailable or too costly.[2]

Figure 3: Examples of our perspective-based reconstruction using simple geometric primitives (images from Petra). On the left are shown single snapshots taken with an ordinary camera with the addition of fiducials. On the right are shown the results of drawing CAD-like primitives as overlays on the basis of perspective cues.

3. Early results

3.1. Gestural and verbal user interfaces

User interfaces developed for production environments have not evolved significantly since the introduction of the windows, icons, menus, and point-and-click (WIMP) interface metaphor over two decades ago. Despite the advantages of WIMP interfaces (e.g., ease of use, short learning curve, and wide applicability), they greatly under-utilize the real-world capabilities and skills of users by limiting input and output to a keyboard, mouse, and monoscopic display. While effective for 2D desktop productivity applications, WIMP interfaces are not the ideal solution for intrinsically 3D applications. In this context, we have undertaken the study and evaluation of the next generation of post-WIMP interfaces that leverage application-specific knowledge and human skills to realize a more powerful, natural, and task-efficient user interface. Gestural and voice-driven user interface is being used for interactively modelling 3D objects in a virtual environment. In figure 3, simple geometric models here are overlaid on a photograph from the site at Petra.

Examples of our recent work are 3D widgets (Brook Conner et al. 1992), free-form deformations (Hsu and Hughes 1992) and gestural interfaces (Zeleznik et al. 1996). 3D widgets demonstrate how parameters can effectively be represented by 3D geometry and embedded in a 3D dataspace. Our system *Sketch* (Zeleznik et al. 1996) is a gestural interface for 3D geometric conceptual design which demonstrates that 2D drawn gestures can specify rich, context-sensitive commands to realize a powerful interface without relying on 2D WIMP user interface mechanisms.

Our most recent and on-going effort, the ARCHAVE[3] project, on the development of a multi-platform interactive virtual environment for archaeological analysis within the context of an accurate reconstruction of the site, both in space and time, is presented elsewhere (Vote et al., this volume).

3.2. Three dimensional reconstruction from a single image

We have conducted preliminary work in order to extend our current *Sketch* system (Zeleznik et al. 1996) to interactively generate and edit free-form 3D shape models in a sequence of images. Figure 3 illustrates our first generation system which makes use of single viewed perspective images (Williamson and Brill 1990) together with basic geometric primitives. Our approach in this stream is to maintain a functional system that is fully interactive using, in the early phases, our current knowledge of 3D shape and scene recovery, and incorporates novel shape models and automated shape recovery algorithms, as they become available in the later phases of this project.

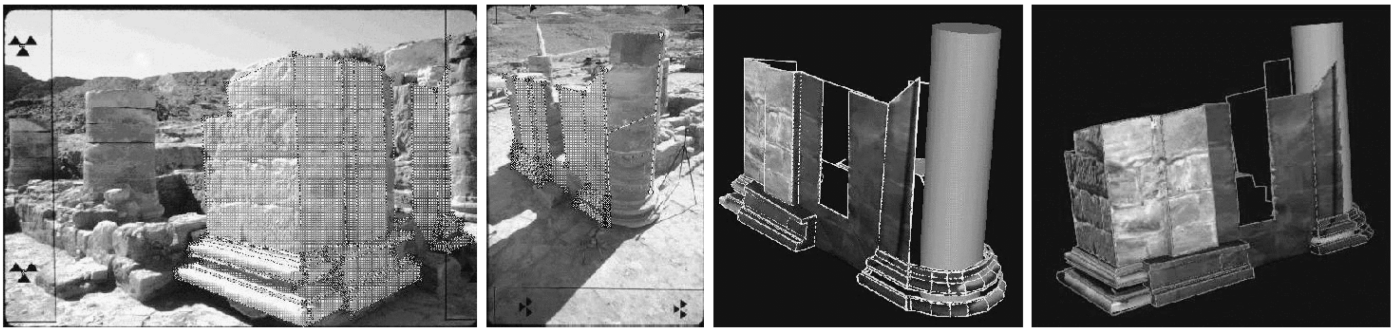

Figure 4: Illustration of photogrammetric 3D reconstruction from multiple images for architectural forms; more details in Vote (1999, in press).

Figure 5: Six images (4 of which are shown) of the face of one of the co-author, D. Mumford, are used to determine its shape. The pose is constant, while the lighting varies. The resulting photometric variation reveals the shape, as shown in the depth map and wire-frame (fifth and sixth pictures).

3.3. Three dimensional reconstruction from multiple images

In order to establish the geometry of a scene and its objects, a number of correspondences (e.g. feature points) need to be recovered between N images of a sequence (Leymarie et al. 1996). In the context of archaeological scenery, corner detectors combined with a model-based approach (for position refinement), prove useful (Blaszka and Deriche 1994). For a video sequence, one can take advantage of the "continuity" of the sequence, by using robust tracking techniques (Leymarie et al. 1996). The correspondence problem is harder to solve for a set of photographic snapshots taken from a-priori unknown positions. This stage is user-driven in classical photogrammetry (Leymarie and Gruber 1997). To automate this task, one can make use of classical (window) correlation-based techniques combined with relaxation methods in an optimisation stage. Given the intrinsic camera parameters, we can then establish the calibration of the sequence (also called "exterior orientation" in photogrammetry). Alternatively, one can recover the full set of parameters, via robust estimation techniques (Faugeras et al. 1995). Once calibration is solved, more feature points can be acquired and matched to generate a cloud of 3D points. Finally, a triangulation can be obtained thanks to methods retrieving the connectivity (topology) of the bounding surface. Such methods permit to obtain realistic renditions of a statue (e.g. at roughly a ±5 mm accuracy in surface deviation). We expect our shape models, to be presented below, to constrain the reconstruction process and greatly simplify the final representation of such free-form objects while maintaining good accuracy.[4]

Similar techniques were applied to photographs taken at Petra and are illustrated in figure 4 where we performed some detailed wall reconstruction under user supervision (Vote, in press). We have also experimented with a "dual" method to photogrammetry, where the camera and object positions are fixed, and, instead, the light source is moved to known positions. This is based on the work of Belhumeur et al. (1996). Note that, this technique bypasses the problem of calibration. However, such a setup provides for excellent accuracy to scan small objects in a constrained environment where lighting conditions can be controlled (see figure 5) and is, thus, comparable to structured light techniques such as used in (Pollefeys et al. 2000).

3.4. Fragment representation and reassembly

The series of detailed head statuary in figure 1 need to be reconstructed by filling-in missing sections, fusing related fragments, reconditioning eroded surfaces and, finally, comparing the shapes of the different heads with others found in the region of Petra (Joukowsky 1998). A similar problem we have solved using IPS models (see section 4.2) by matching 3D fragments of an Egyptian bust (Blane et al. 2000). The use of ridges and skeletal graphs for the same purposes represent on-going work, and more details about these methods are given in section 4.1 and section 4.3 below.

3.5. Site content discovery via 3D geometric history

For analysis, it is essential to maintain the artefacts in their architectural and topographical context. Following what Forte (2000) proposed, we have started exploring how Geographical Information System (GIS) (Kofler et al. 1996) and Virtual Environments (VE) can be useful in helping archaeologists understand their data to develop new conclusions and hypotheses about the history and evolution of the Nabataean culture (Vote et al., this volume).

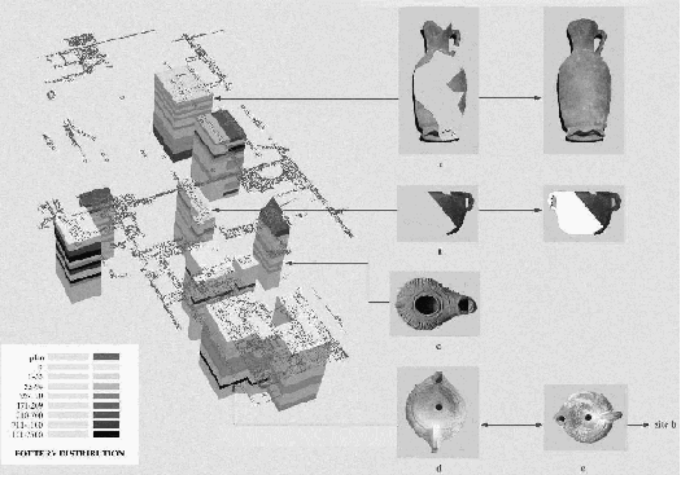

Figure 6: GIS application at Petra's Great Temple. Artefacts referenced and defined in 3D will allow archaeologists to reconstruct objects (a and b), do advanced spatial analysis, link artefacts between sites (For example, tracing lamps between sites in the region will allow us to trace trade routes.) (c, d and e), and maintain more comprehensive, accurate and accessible records of artefact geometry and find locations.

Figure 6 shows a GIS application with a 3D view of trenches. Colour represents the concentration of pottery fragments found in each locus or layer of excavated material. Unfortunately, the "traditional" GIS cannot represent in 3D the in situ or find position of individual artefacts or allow reference to specific finds on site or in other sites around or outside of Petra. With the ability to reference the location and geometry of artefacts, archaeologists will have a more dynamic data set that can be used to reconstruct, link objects for analysis and maintain spatial information for future generations. This is explored in our ARCHAVE project which is described in detail elsewhere (Vote et al., this volume).

4. Three dimensional free-form shape modelling

We have been investigating the use of 3D distinct representations for shape, i.e., ridges, implicit polynomials and skeletal graphs. Our premise is that these representations are intimately connected (e.g. see figure 10b), and we propose a joint, integrated, and comprehensive investigation of these, which shall lay the foundations to establish a complete and formal shape language for general use in archaeology and beyond. Briefly, *ridges* are a representative of curve loci on a surface, a one dimensional construct in space, e.g., a break curve where a sherd was broken from another piece. *Implicit polynomial surfaces* (IPS) are a representative of entire surface loci, a two dimensional construct in space, e.g., the outer and inner surfaces of a pottery sherd. *Skeletal graphs,* also called *Medial Axes (*Blum 1973), are a representative of volumetric features, a three dimensional construct in space, e.g., the main axis of a pot and its symmetric relations with the pot surfaces. These three elements are constitutive of a vocabulary classification for shape. Their relationship via a hyper-graph structure, will define the equivalent of a syntax for 3D shape. In the remaining of this final section we detail each vocabulary class.[5]

4.1. Curvilinear modelling through ridges

What are ridges? It is simplest to define them in 3D by analogy with a 2D case. The boundary of a 2D shape is a simple closed curve which can be divided into convex and concave portions, separated by points of inflection where the curvature of the boundary vanishes. In addition, there are special points on the boundary where the curvature has a local maximum or minimum. The most important of these are the "vertices": local maxima in convex segments, and local minima in concave segments, which are analogs of the vertices of polygons. In particular, each endpoint of the medial axis or skeletal graph (see section 4.3) of the shape is the centre of the osculating circle at a convex vertex (Leyton 1992) (see figure 9a and 9d). The psychologist Attneave proposed that these were the most perceptually salient and informative points on the contour (Attneave 1954).

What happens in 3D? The situation is more complex. Instead of merely convex and concave pieces, the boundary of any 3D shape is divided into three kinds of pieces: (i) the convex parts with both principal curvatures positive, (ii) the parts where both principal curvatures are negative, i.e., the surface is strictly concave, and (iii) the hyperbolic saddle-like parts where one principal curvature is positive, the other negative. Instead of local max and min points for the principal curvatures, one looks for curvilinear collections of points where the larger of the two principal curvatures has a local max on its corresponding *line* of curvature (figure 7a), and points where the smaller curvature has a local minimum. The *ridges* in the *convex* parts of the surface are smooth analogs of the convex edges of a polyhedron and are perceptually salient as the prominent lines where the surface *protrudes*. Likewise, "ridges" in the *concave* parts of the surfaces look like the bottom of *valleys* where the surface is *creased* (Cipolla et al. 1995).

One goal is to use these features to describe 3D shape in an intuitive way. In figure 7b, ridge computations on a sherd surface data obtained via CT scanning (cf. figure 2) are depicted as different shades of grey corresponding to different measures of extremal curvature. We have developed an interactive algorithm to extract ridges and valleys based on this curvature map; this is illustrated in figure 7c. The user clicks a starting point and goal (which may be identical, to close a loop), decides whether a ridge or valley is needed, and then lets the computer rely upon an implementation of a 3D active contour to seek an optimal path (Leymarie and Levine 1993). Such an active contour model tends to minimize a cost function based on an integral of the curvature measures along a path as well as on measures of elastic tension along the contour. Because such features as ridges and valleys correspond well with (human) intuitive curvilinear descriptors for free-form shapes, we believe they will provide a very effective tool for manipulating shape for interactive modelling as well as for indexing and searching databases of shapes, and delimiting break surfaces of sherds.

The next stage in our research program is to explore the use of ridges/valleys on a variety of free-form shapes, bodies and a range of artefacts as well as faces, animals, humans, sculptures of various types, furniture and tools, etc. There has been psychophysics on the human perception of ridges (Phillips 1997) and an additional goal is to characterize how *stable* ridges are for shape modelling.

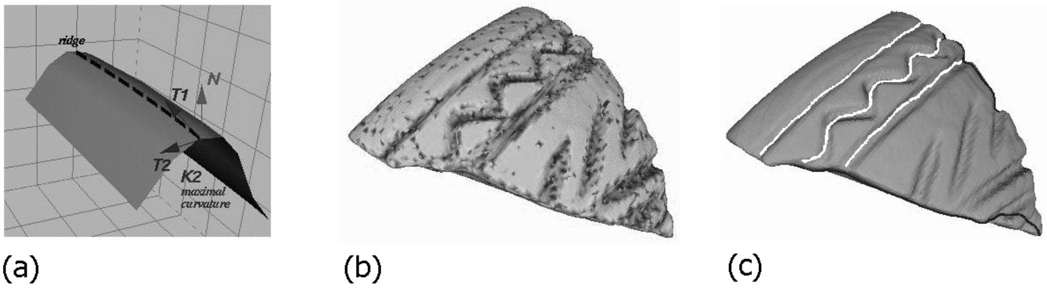

Figure 7: (a) Concept of a ridge as a line of maximal principal curvature on a surface. (b)Local curvature computations on a sherd from its recovered 3D surface. (c) Result of an interactive ridge and valley computation using a 3D active contour model (see Andrews 2000 for more technical details).

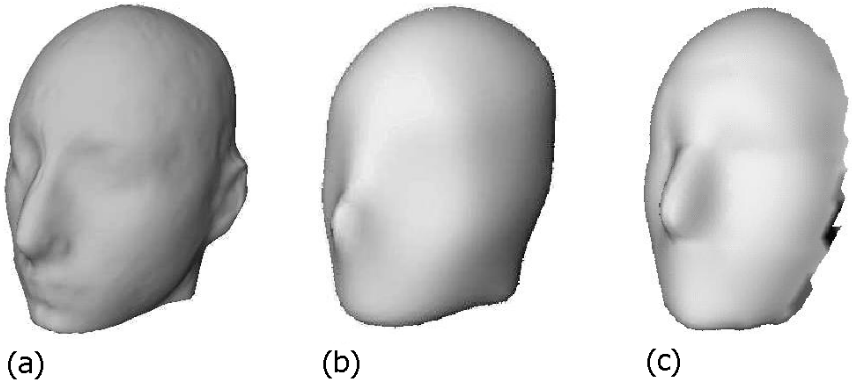

Figure 8: (a) Original triangulated head data set. (b) 10th degree fit (ears discarded). (c)Reconstruction via 12 patches, using 4th degree IPS for each patch.

4.2. Surface modelling through implicit polynomials

Multivariate Implicit Polynomials provide a powerful and rich representation for 2D and 3D curves and surfaces (Bloomenthal et al. 1997). For example, a trivariate dth degree Implicit Polynomial Surface (IPS) is the zero set of a dth degree explicit polynomial, i.e., the set of points (x,y,z) where the explicit polynomial is zero, $f(x,y,z) = \sum_{i+j+k \leq d} c_{ijk} x^i j^j z^k = 0$. These surfaces are generalizations, to more complicated shapes, of the conics, e.g., a hyper-ellipsoid, a cylinder with hyperbolic cross section, etc.

For example, the set of points (x,y,z) for which $(x-x_0)^2+(y-y_0)^2+(z-z_0)^2-R^2 = 0$ is the equation of a sphere of radius R having centre $x = x_0$, $y = y_0$, $z = z_0$. These IPS are useful for representing blobby closed surfaces, open patches as in figures 1, 4, 6 and 8, surfaces attached to prominent ridges, generalized cylinders (Naeve and Eklundh 1994), and other shapes, e.g., free-form shapes with holes. IPS can be used in at least two interesting ways: (i) as a coarse, but smooth, approximation or (ii) as a close fit to the data. As a low resolution approximation to a complex surface, an IPS can be used to extract coarse geometry useful for shape recognition, crude assembly of fragments into reconstructions, etc. On the other hand, a single high degree IPS or a number of patches made of IPS of more modest degree, can be used for a high resolution representation. Some of these uses are illustrated in figure 8.

A goal of our research program is to explore the use of ridges (section 4.1) and skeletal graphs (section 4.3) for the optimal placement of IPS patches so that low order fits, and thus fewer parameters, can be used. Fitting to data is fast, repeatable, and robust, since the fitting is linear least squares (thus resulting in an *explicit* expression for the estimated coefficient vector), it is regularized by our 3L fitting (Blane et al. 2000), and is further regularized by the use of *ridge regression* (Blane et al. 2000). Note that, the principal computational cost is in computing only a scatter matrix of monomials based on the (x,y,z) data points. Once this is done, a refitting to subsets or unions of data point sets, or a modification of surfaces through human interaction, requires orders of magnitude less computation and is possible in real-time.

Our approach to human interaction with shape, when using IPS, is to modify the surface much as a sculptor or a designer might: by specifying a position, or a position and a tangent cut, or a position, a tangent cut and two bendings (e.g. via principal curvatures) that we want the deformed surface to satisfy approximately (soft constraint) or exactly (hard constraint), such that the surface is not modified much away from the position of interest. More generally, we can specify a number of points, or a curve in 3D, or a surface attached to a ridge that we want the deformed surface to approximate.

Our next step will be to investigate a hybrid model by interpolating with an IPS exactly (hard constraint) or approximately (soft constraint) by specifying some surface properties (e.g. curvatures, tangents, etc.) in-between the ridges, where these latter properties could be specified through stochastic processes or through probability distributions. For elongated surfaces like an arm, perhaps an upper torso, an elephant trunk, etc., a *generalized cylinder* (Naeve and Eklundh 1994) can be realized by computing the skeletal axis of skeletal sheets (see below), and then sweeping a cross-sectional planar IP curve along the axis, where the plane is

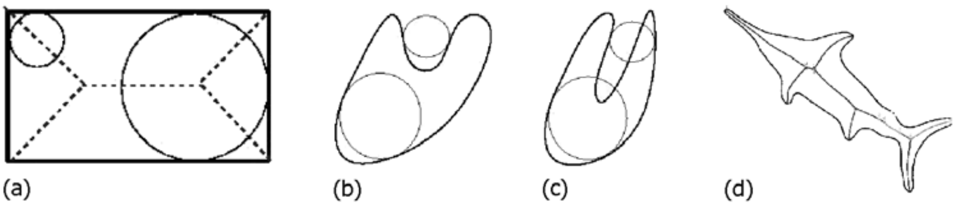

Figure 9: 2D skeletons: (a) Skeleton of a rectangle with two examples of maximally inscribed circles; (b) example of two bitangent circles which are maximal and (c) two which are not, since they cross the boundary; (d) More complex skeleton for a swordfish outline - note that at each curvature extremum of the boundary corresponds the end of a skeleton branch.

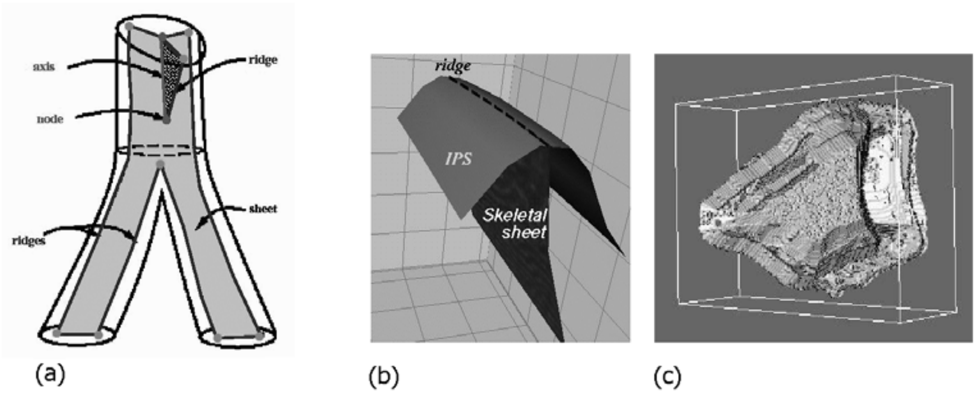

Figure 10: (a) Sketch of the 3D skeleton of a branching shape: the skeleton is made of sheets, axial and ridge curves, and nodes. (b) Concept of skeletal sheet and its relation to IPS and ridges. (c) Computed skeletal sheets of a carpal bone.

orthogonal to the axis and has a local coordinate system determined by the skeletal sheet.

4.3. Volumetric modelling through skeletal graphs

The skeletal graph of a 2D shape, or its medial axis, is the locus of centres of *maximally inscribed circles* (see figure 9). It is an intuitive and efficient representation for the recognition of 2D shapes, since variations in shape often leave the graph structure intact (Blum 1973). This medial axis graph structure, however, maps to a variety of shapes (i.e., by varying its associated radius function) and thus is not sufficiently constrained to reveal qualitative shape. A dynamic view of the skeletal graph as the singularities (shocks) of wavefronts propagated from the initial boundary (Leymarie and Levine 1992) defines a notion of velocity and direction of flow for each medial axis point and thus leads to a finer partitioning of the skeletal branches at points where the flow is reversed. The resulting shock graph, when stripped of radius information, is more discriminating in that it reveals qualitative shape (Kimia et al. 1995).

Shape can be fully reconstructed from the medial axis and the corresponding radii as the envelope of circles centered on the axis. The local nature of this intimate connection between shape and skeletal graphs, however, is not explicit in the envelope reconstruction. In (Giblin and Kimia 1999) the differential geometry of the boundary, i.e., tangent and curvature, is derived as a function of the differential geometry of the medial axis and of the dynamics of shock propagation on the axis, i.e., velocity and acceleration. It is shown that the shock graph, together with curvature and acceleration descriptions for each link, is a complete description of shape.

For 3D shape, the medial axis is the locus of *maximal bitangent spheres*. The wave propagation approach again leads to a dynamic view of shocks propagating on the skeletal locus (Leymarie and Kimia 2000). The points of medial axis (and shock set) have been classified resulting in a hypergraph representation (Giblin and Kimia 1999) consisting of skeletal sheets with associated flow fields, which end either at a boundary corresponding to *ridges* or at curves shared by three medial sheets, much like the central axis of a *generalized cylinder* with a triangular base (Naeve and Eklundh 1994). These curves interact only at special points, namely when they intersect each other at nodes. These are the only generic possibilities (figure 10). The skeletal hypergraph describes the connectivity among symmetries of each portion of the shape (see Leymarie and Kimia (2000) for more details).

The next step in this research is to investigate how the skeletal hypergraph can be matched against other medial axis representations in a pre-stored database of similar objects, in analogy to 2D matches (Sharvit et al. 1998). Also, partial matches of skeletal axial curves should prove useful to solve the difficult problem of automatically stitching together different sherds to recover a full pot (Ucoluk and Toroslu 1999).

5. Conclusions

The SHAPE Lab has been created with the goals of: (i) introducing new geometric modelling and 3D surface and structure recovery from images; (ii) improving human/machine interaction tools for facilitating human input of geometric information to the machine and then visualizing the results in real time; (iii) developing new tools to facilitate reconstructing large geometric structures (e.g., walls of buildings) and smaller objects (e.g., columns and their capitals, and at more detailed levels, with statues and artefacts) from free-form fragments scattered about a site. These objectives require considerable domain-specific knowledge and are central in providing material for analysis in archaeology but also can be used extensively in architecture and architectural history, and ultimately in many other disciplines where the design and manipulation of free-form 3D shapes is required.

In order to fulfil this ambitious program, a key component is the development of a shape language for 3D free-form objects. We have reported in this paper on our early success in putting together a vocabulary based on three classes of elements: *ridges*, to model perceptually significant surface curves, *implicit polynomials*, to model surfaces of various complexity, and *skeletal graphs* to model volumetric features and, furthermore, provide the "glue" to relate together the three classes.

Difficult and interesting challenges still remain ahead of us. There is clearly a *continuum* from the ridges on polyhedra which are most precise as well as most salient and those in near planar or near spherical parts of the surface, and this "scale-space" for ridges needs to be studied (Mumford et al. 1999). A second question is how to *approximate* a 3D shape using ridge and skeletal data. In the plane, an old idea going back to Attneave is to approximate any 2D shape by the polygon joining its vertices. What analogs of this construction can we make in 3D? An essential step in the HCI part of this research (section 3.1), is to be able to estimate an entire shape roughly based on the user marking approximate ridges and local planes of symmetry, and then let the computer position and select implicit polynomial models of the surface patches bounded by such ridges. Another question concerns the location of ridges using reflectance data gathered from one or more images of an object. The basic idea is that since the tangent plane is changing rapidly at ridge points, images of the surface will have rapid changes in intensity along ridges. In addition, specularities "cling" to ridges and with elongated light sources, may even make the whole ridge shine. We want to make these ideas precise and integrate them in the reconstruction of 3D shape from multiple images with varying illumination as a constraint used in the recovery of shape (figure 5).

In addition to developing this approach to shape representation, we want to apply it to object recognition based on shape. It is broadly recognized that one of the most effective techniques for object recognition is the use of Bayesian statistical methods (Cernuschi-Frias et al. 1989). In order to apply this method to free-form shapes, we need priors of the space of such shapes (Mumford 1996). For example, the shapes we find are often built out of parts which may be generalized cylinders or rectangular parallelepipeds; or they may have limbs like a statue, a human or a tree in winter, etc. The approach we want to take is to model stochastically the generic features of shapes, their skeletal graphs and ridges and decomposition into parts. In 2D, Zhu and Yuille (1996) have constructed stochastic models of shapes based on the medial axis. In 3D the development of such priors, involving the explicit representation of ridges and skeletal graphs, is needed.

Acknowledgments

Major funding for this project comes from the USA NSF/KDI grant #BCS-9980091. Frederic Leymarie was partially supported by a Ph.D. fellowship from IBM. Besides the co-authors, a number of students and researchers have been involved in the first year of the SHAPE Lab and have had a major impact on the work reported in this paper. These include graduate students Daniel Acevedo, Stuart Andrews and Jill Baker, Dr Peter Giblin (Liverpool) and Dr Jean-Philippe Tarel (Paris).

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Notes

[1] SHAPE: SHape, Archaeology, Photogrammetry, Entropy; a multidisciplinary project established in the Fall of 1999; visit our website at: www.lems.brown.edu/vision/extra/SHAPE/.

[2] N.B., we also plan to relate and compare objects and aspects of our site with other sites within Petra and other Nabataean sites like Medain Saleh.

[3] ARCHAVE: ARCHAeology with Virtual Environment systems; see (Vote et al., this volume).

[4] Such a model-based constraint paradigm is similar to Debevec et al.'s, earlier DARPA community's and others' approach to 3D reconstruction from images. However, in these other approaches, much simpler set of models is used. These simpler models are typically made of regular primitives to represent simple architectural shapes (Streilhen 1994).

[5] The syntaxic properties of our shape language will be reported elsewhere; see (Giblin and Kimia 1999) for early theoretical investigations.