RETURN

CONCEPT OF A SYSTEM FOR THE COMPUTER-AIDED RECONSTRUCTION OF ANTIQUE MONUMENTS

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ABSTRACT

This paper investigates the possibility of a computer-aided system for the archaeological reconstruction of monuments. It analyzes the entire workflow of reconstruction for steps which are suited for computational solutions and gives a concept for the implementation of these steps in a computer program using the tools of spatial data processing.
In order to accomplish this task the necessary preconditions and input data for the program are established, a data model is applied to organize the occurring objects in a relational database system and algorithms are presented for the computation of the most likely reconstruction out of the input data using successive negative selection.
The concept was implemented in a prototype version and verified with small test-datasets.
A final evaluation is not yet possible, but the results of the performed test-runs seem to confirm the concept, provided that the input data allow a reconstruction with regard to the original positions.

KURZFASSUNG

In dieser Arbeit wurde die Möglichkeit der EDV-Unterstützung von archäologischen Gebäuderekonstruktionen untersucht. Es wurde festgestellt, welche Arbeitsschritte im Gesamtablauf der Rekonstruktion sich für eine Lösung mittels EDV eignen und ein Konzept für die Umsetzung dieser Arbeitsschritte in einem Programmsystem mit den Mitteln der räumlichen Datenverarbeitung erstellt.
Dazu wurden die notwendigen Voraussetzungen und Eingangsdaten definiert, ein Datenmodell für die Organisation der vorkommenden Objekte in einer relationalen Datenbank festgelegt und Algorithmen angegeben, um durch sukzessive Negativauswahl aus den Eingangsdaten eine möglichst steingerechte Rekonstruktion des bearbeiteten Gebäudes herzustellen.
Das Konzept wurde in einer Prototypversion implementiert und anhand kleiner Testdatensätze überprüft.
Eine abschließende Beurteilung ist zum gegenwärtigen Zeitpunkt noch nicht möglich, die Ergebnisse der Testläufe scheinen das Konzept jedoch zu bestätigen, immer unter der Voraussetzung, daß die Eingangsdaten für eine steingerechte Rekonstruktion geeignet sind.

INTRODUCTION

Archaeologic Reconstruction

In the context of constructional science and preservation of monuments on archaeological excavation sites arises the problem of reconstructing broke-down monuments from their excavated pieces [Schmidt 1993]. Such reconstructions are needed as a scientific measure to learn details about the buildings and the building process, to help preserve the material, and of course also for tourism purposes, since a reconstruction is more interesting for non-experts than pieces in disorder [Hueber 1985].

According to the principles of modern constructional science the reconstruction should be carried out taking into account the single pieces, placing back every piece to its original position within the overall structure of the building. The reconstruction process can then be divided into two parts: the first one is to find the overall form and structure of the building and the second one to find the individual stones' positions in this general reconstruction plan. These two steps are not completely independent of each other. The first step can only be carried out based on an overview of the existing stones, and the second step may demand changes in the buildings overall structure. Still the division proved to be useful.

The first step requires a great amount of expertise in constructional science, architecture and art history, furthermore knowledge about the use of the building and the circumstances of its excavation [Hueber 1978]. This task can only be accomplished by an expert, and due to its structure it is not very well suited for automation. This part of the reconstruction is *not* treated in the following. The existence of such a "reconstruction plan" is assumed as a prerequisite for the automation of the second step.

In the second step we search for the individual position of each existing building-piece. The pieces are treated as individuals, whereas in step one their individual differences were deliberately disregarded in order to group them and thus simplify the task. The problem consists in assigning each existing piece to one piece of the general reconstruction plan. The information that can be used to identify the position is: attributes like the precision of the stone-cutter work and ornaments on its surface. An important source of information is the original position on the excavation, which unfortunately was often lost, especially on older sites.

These attributes also provide information about the relative position with respect to the stone's neighbors, for example when an ornament continues on the neighboring piece. Additional information about the relative positions can be found in constructive details, such as clamps and plugs made of iron, that where used to fix pieces together when working without mortar (see figure 1) [Müller-Wiener 1988]. The clamps and plugs are normally not available, because they were removed for further use of the material right after the building broke down. However the holes where they were fixed to the stones remain there.

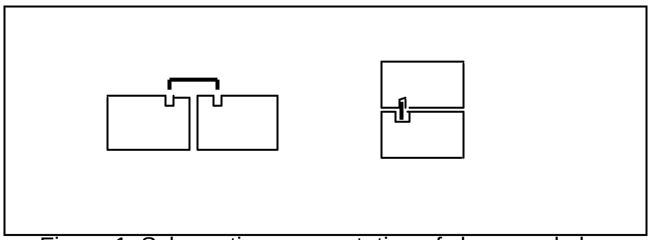

Figure 1: Schematic representation of clamp and plug

One more important source of information is the exact geometry (size and form) of the piece, since slightly different pieces will fit better or worse in the gap between a number of other pieces. This information can only be used in an overall approach fitting together *all* the pieces at once, because moving one piece implies moving its neighbor, since building-stones are not elastic.

These geometric constraints make the reconstruction with respect to the pieces slow and expensive. To find the best-fitting piece, different possibilities have to be compared by actually bringing stones into their relative positions using a crane.

Computer Support

To overcome these difficulties one can try to build a computer-model of the building and of the material and simulate the reconstruction in a faster and more efficient way, with the possibility to try out a greater number of reconstructions. For computer-simulation of a real-world situation the relevant objects and the actions to perform on them have to be made accessible to the computer, describing the objects by data and the actions by algorithms.

The data in this case are the dimensions and attributes of the building pieces and the general reconstruction plan. The dimensions are normally measured on the excavation-site, the attributes can be interpreted by a skilled person. The reconstruction plan has to be provided by an expert, as described above.

In the following the possibility of a computer-assisted reconstruction with respect to the individual pieces is discussed, giving a data-model for the organization of the input-data and algorithms for their processing.

Testdata

The investigation was proposed by the *Austrian Archaeologic Institute (ÖAI)* and *AVT-surveys Tirol*, a private company involved in the surveys of the ÖAIs mayor excavation site in *Ephesos/Turkey*. For this reason, the test-data used for this paper are based on the so-called *Octogon*, a hellenistic tomb of an unknown noble person in Ephesos [Alzinger 1974, Thür 1990].

DATA MODEL

This chapter gives an overview of the necessary objects, followed by a description of the structure of a building stone.

Objects

Real Stones. We call the really existing stones that were found on the excavation "real stones" (see figure 2).

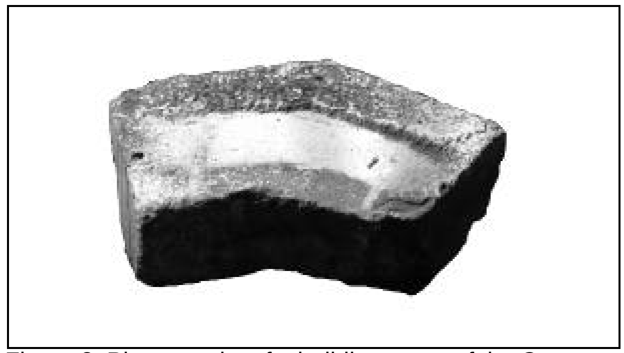

Figure 2: Photography of a building stone of the *Octogon*

Their description consists of two parts. Geometry is described by measurement data. Qualitative information is described by attributes. In the following the stones are assumed to be polyhedrons bounded by planes. This simplification is justified by the fact that the faces along which two stones touch, are generally planes, and the other faces only have to be rough approximations.

The measurement data can be taken from photogrammetry or from any other spatial measurement technique. In any case this point-data will not produce ideal planes, due to limited precision in the production of the pieces, but also to deterioration with time. Therefore best-fitting, ideally plane "cover-solids" are circumscribed by the means of adjustment calculus (see figure 3). These cover solids represent the real stones, the original data is no longer needed. The holes for clamps and plugs are also projected onto the cover solids.

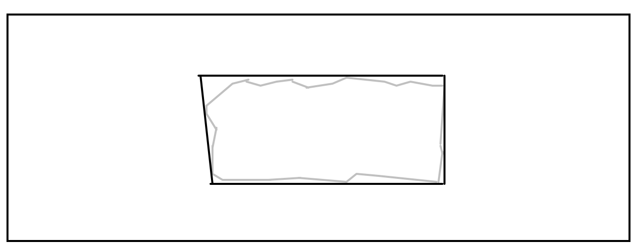

Figure 3: Schematic representation of a real stone (grey) with its cover-solid (black)

Stone Types. Due to the great number of symmetries in common buildings and due to the serial production of building pieces we generally find groups of stones, that should have the same size and form. Actually, the members of such a group differ slightly, be it as a result of the limited working-precision of the stone-cutters, because of corrections done on purpose and/or because of the weathering of the material. Such a group of stones is referred to as a "stone type".

The definition of stone types already is the first step of classification. When making up the general reconstruction plan in the first step of reconstruction, the archaeologist uses a limited set of stone types, disregarding the individual differences, which serve to find the individual positions in the second step.

Ideal Stones. The identical copies of a stone type, which make up the reconstruction plan, will be called "ideal stones". They are the ideal exponents of the stone type.

An ideal stone can be created in two different ways. If real stones of its stone type exist, the ideal stone is derived from them as a "mean" of all the real stones, with additional constraints to achieve a polyhedron with the desired ideal angles (see figure 4). If there are no real stones - this means, that the archaeologist has postulated a type, although none of its exponents was found -, the geometry has to be defined during the definition of the stone type, since there is no information available.

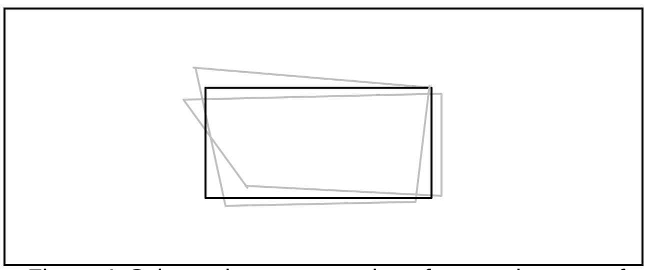

Figure 4: Schematic representation of two real stones of the same type (gray) and the mean stone of their stone type (black)

The Reconstruction Plan. The "reconstruction plan" is the – preliminary – result of the first reconstruction step, a model of the building consisting of ideal stones. During the second reconstruction step it can turn out to be necessary to modify the reconstruction plan. Then the second step has to be repeated, leading to an iterative refinement procedure.

Data Structure

The stone, the fundamental object, is made up by its faces, edges and corners, which also are used to encode the neighbour-relations.

Points-the Metrics. The dimensions of a stone are stored as coordinates of its corner points. For real stones these are the coordinates of each individual cover-solid, given in an *individual coordinate system* (see figure 5). They therefore only define then stone's size and form. For all ideal stones the coordinates are stored in *one global coordinate system*, valid for the whole reconstruction plan.

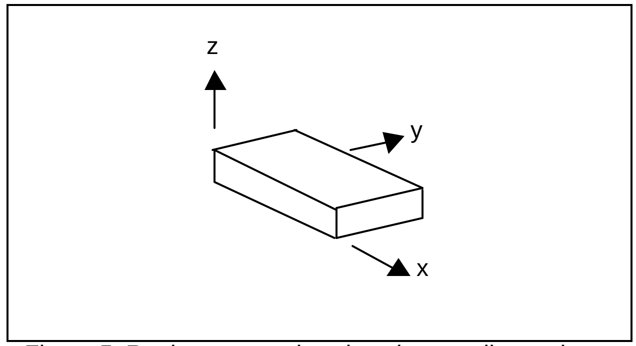

Figure 5: Real stone metrics given by coordinates in an individual coordinate system

Edges - Topology. Each stone inherits the topology from its stone-type. Topology is defined in a data-structure based on the edges, the so-called "winged-edges"-model [Kirschenhofer 1995]. In this model every edge has a *direction*, enabling to connect it to the faces by storing its "left" and its "right" face (see figure 6). This – originally two-dimensional – data model can be applied to spatial objects, if two conditions are fulfilled: The objects must to be closed volumes (as are the stones), and a direction of observation must be defined in order to give meaning to the expressions "left" and "right". All objects have to be observed from the same side, either from inside or from outside [Schindler 1999]. For the stones of course observation from outside was used, as we are used to this way perception.

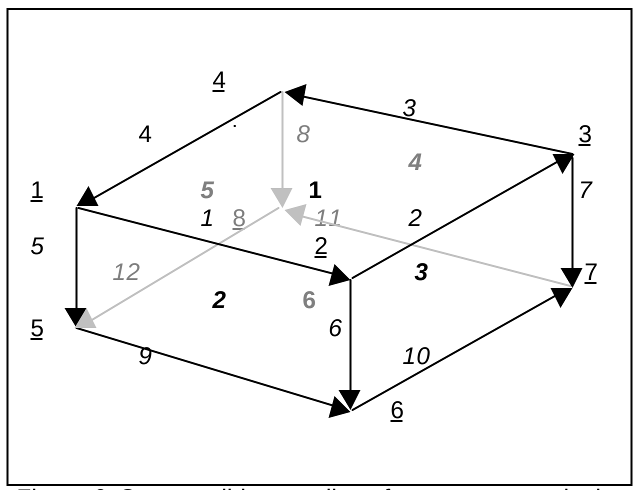

Figure 6: One possible encoding of a square-stone in the "winged-edges" model

Faces – Attributes. Attributes assigned to the faces store the qualitative information such as for example orientation (whether it is the stone's top-face, bottom-face or a side-face) or exposure (whether the face was visible to spectators and therefore planed carefully or invisible and therefore only roughly worked).

All attributes of all faces of the ideal stones can be derived from their positions in the reconstruction plan, whereas the attributes of the real stones are only partially known, depending on what the archaeologist can discern.

Constraints On Stone-Boundaries. Some of the real stones have holes for the constructive elements (clamps and plugs). These holes represent geometric conditions: the stones must lie in such a relative position that it would be possible to insert the clamp or plug (see figures 1 and 7).

Neighbors – Relations Between Stones. Two stones are called neighbors, when a face of the first stone and a face of the other stone touch. The neighbor-relation can therefore be described by giving the two touching faces and two shifts and one rotation between the stones in a two-dimensional coordinate system in the common plane.

All positions of ideal stones in the reconstruction plan are known, therefore all neighbor-relations between ideal stones can be derived from the input data. There can also be known neighbor-relations between real stones (e.g. when an ornament continues from the surface of one stone to the next one, the archaeological operator will be able to classify the two stones as neighbors). The operator can input this information, forcing the two stones to be placed in a way that their relative position is preserved.

WORKFLOW

After introducing the data, this chapter gives an overview of the main steps of processing that have to be applied to it in order to simulate reconstruction.

Input

Input already forms part of the data processing: from the operators input new data objects are automatically created and then used as input for the next step of operator input. All these steps together form an interactive process of data definition for the subsequent reconstruction process.

Real Stones. Starting from photogrammetric measurement, the cover-solids can be calculated in a highly automated process and the resulting corner-coordinates can then be directly used to store the stones geometry. Attributes, as the result of interpretation, have to be input manually by the operator.

Stone Types. The decision, which types to define, is left to the operator, although in a later stage an automatic classification based on geometric similarity criteria may be possible [Kraus 1990]. To define a stone type, the operator identifies an arbitrary real stone of that type as an example, then the topology can be generated automatically. Having declared all stone types that can be found among the real stones, the operator has to assign every real stone to one of these stone types and give the geometric constraints to achieve the desired form. Then the geometry of the stone type can be found automatically.

Stone types that do not exist among the real stones – i. e. the operator postulated a stone type that he believes to be necessary for the reconstruction – have to be created without automatic support, as there is no data on which to base the support.

Ideal Stones. After creating all stone types, the operator only has to give the number of ideal stones of each stone type needed for the reconstruction plan, and the ideal stones can be easily provided, as they are identical copies of the stone types idealized “mean”.

Reconstruction Plan. With this complete set of ideal stones the reconstruction plan can be coded: a global coordinate system is defined, then all ideal stones are brought to their position by shifts and rotations. As long as there is no graphic CAD-type interface most operators will prefer to start with one (arbitrary) stone and encode the reconstruction plan by giving a sufficient number of neighbor-relations instead of directly giving the translations and rotations for each stone. The input - and also the data processing - can be further improved for many buildings by dividing them into layers which are then stacked onto each other to achieve the complete reconstruction plan (the division into layers corresponds well with the cognition of the expert who creates the reconstruction plan).

Reconstruction

Starting from the (very general) asumption that every real stone has to correspond to one of the ideal stones in the reconstruction plan, the task of finding possible reconstructions can be split into three parts: First of all the stones run through a process of negative selection to discard all assignments that do not fulfill all conditions of similarity. Secondly the constraints given by neighbor-relations have to be checked, resulting in a list of conditions to be observed when permutating the real stones to complete reconstructions. Finally a list of possible complete reconstructions has to be generated based on these two sets of conditions and for each of these reconstructions a measure of quality has to be calculated to be able to compare them.

Assigning Single Stones. The following two conditions have to be met by a real stone and an ideal stone, otherwise the two pieces cannot correspond: Firstly, they must obviously be both of the same stone-type. Secondly, their attributes must correspond (e. g. a face of the real stone, that was identified as its top face, can only occupy the position of the top face of the ideal stone). As soon as the first contradiction is detected, the assignment between the real stone and the ideal stone can be discarded.

Neighbor-Constraints. From the neighbor-relations and the constructive elements a set of conditions can be derived. These conditions of the form “if piece A is placed in position X, then piece B must be placed in position Y” or “ if piece A is placed in position X, only the pieces B, C or E may be placed in position Y” must be obeyed when permutating the pieces to complete reconstructions (see figure 7).

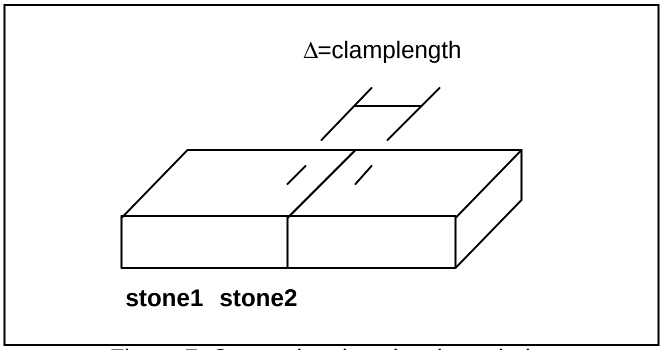

Figure 7: Constraint given by clamp-holes.

Operator's Interventions. To control the process according to his/her intentions, the operator may wish to introduce further restrictions. This is especially necessary in order to be able to try out certain possibilities that are of particular interest at a given stage.

Furthermore this step can be used in the case that too many reconstructions are possible. The process then becomes a computer-aided trial-and-error method.

Complete Reconstruction Models. From the list of possibly corresponding stones the list of complete reconstruction models can be derived automatically using a non-binary tree algorithm with the additional conditions mentioned above and the further condition that every real stone may only be used once in one reconstruction [Schindler 1999].

Comparing Complete Models. The complete models are optimized by the means of adjustment calculus – which here means finding the best way of distributing the remaining inaccuracies and errors, so that the total inconsistency becomes a minimum [Sünkel 1993]. For this task the adjustment is organized as follows: the coordinates of the ideal stones in the global system of the reconstruction plan serve as approximate values for the real stones' points. The single stones are transformed to the global system calculating the three shifts and three rotations per stone for all stones in one single operation. This spatial similarity transformation is applied without scale to preserve the real stones dimensions. To force the stones together as neat as possible, a connecting plane is defined for each stone boundary. All points of the two touching faces are elements of this plane.

Furthermore a system of dynamic weight-factors (similar to the one used for robust estimation) has to be used in order to avoid that stones penetrate each other [Schindler 1999].

As additional conditions for the adjustment, information about the form of the building can be taken into account [Kraus 1996]. One typical example for such form-information is that the border plane between two brick-layers must be horizontal. Another one may be that all faces that are part of the same facade should lie in one plane.

A measure for the remaining errors after adjustment, such as the root mean square deviation of corner-coordinates, is used to judge the quality of a reconstruction.

PROTOTYPE

The concept was implemented as a small prototype to test the developped algorithms (see figure 8). The software-tools used for the prototype are MsAccess, a SQL-based relational database [Schrefl et al. 1995], the developping language VBA (Visual Basic for Applications) [Becker 1997], and the photogrammetric adjustment program ORIENT [Kager 1995]. MsAccess provided the data-managment and the interface, VBA was used to overcome the limitations of SQL and to organize the comunication between MsAccess and ORIENT, and ORIENT served as a powerful tool for the complex mathematical operations.

The idea of this prototype was to build a test-engine rather than to prepare a professional software-product. It is therefore not yet possible to test it on a full-scale real-world reconstruction problem, which would involve a lot of further programming-work. Until now, only small sets of synthetic test-data based on the pieces of the octogon were used.

SUMMARY

The aim of this work was to investigate, in which way the process of archaeological reconstruction can be assisted by a computer system and to give a concept for the design of such a system. The problem of reconstruction was examined for steps that are suited for computer-support.

The reconstruction with respect to the individual building-pieces was found to be suited best for automation. A data-model for the organization of this step in a database-system was proposed and algorithms were given for the processing of the data.

The concept was tested with a little prototype implementation and small synthetic data-sets.

However the effort for the solution of the problem has turned out to be bigger than expected. A long-term project would be necessary to complete it.

Before starting such a project a closer examination would have to clarify the exact range of applications. In this context the necessary amount of input data were estimated. These estimations should serve as a base for more detailed investigations about the necessary input. The result could be compared with actual reconstruction projects as well as reconstructions that were already done. If the necessary data can be provided, the concept should be applied to real-world problems. If not, the additional information used in the conventional way of reconstructing monuments has to be identified and added to the concept, and the existing reconstructions have to be critically reviewed.

One important secondary result of the work is, that very little systematic investigation on the accuracy and reliability of existing reconstructions can be found.

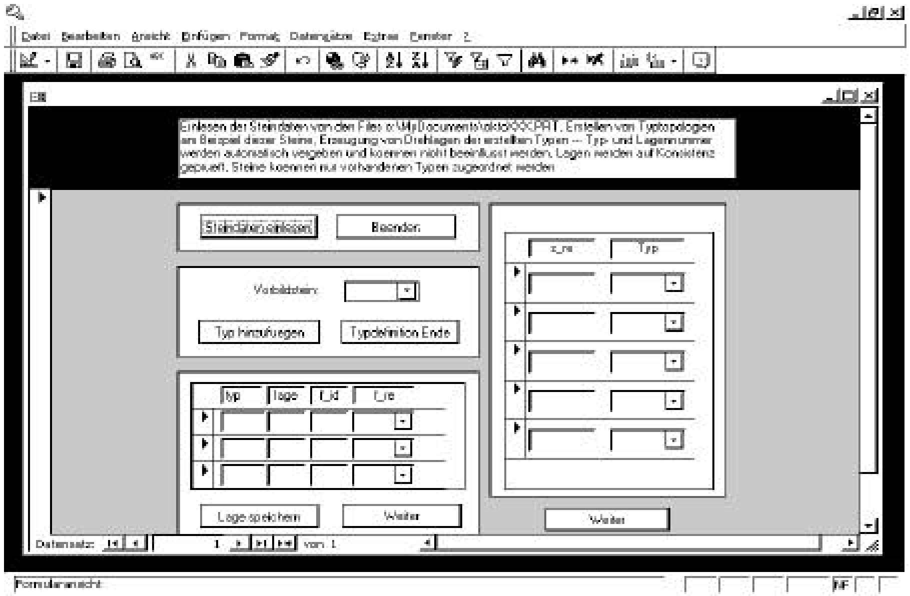

Figure 8: Screenshot from the prototype's input routine

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