HELSINKI UNIVERSITY OF TECHNOLOGY

Department of Surveying

Institute of Photogrammetry and Remote Sensing

Photogrammetric Documentation in the Archaeological Excavation Process – Case: Finnish Jabal Haroun Project

Hanne Junnilainen

2007

Photogrammetric Documentation in the Archaeological Excavation Process – Case: Finnish Jabal Haroun Project

Master's Thesis submitted at the Helsinki University of Technology in the Department of Surveing

Espoo, May 2007

Hanne Junnilainen

Supervisor: Prof. Henrik Haggrén
Instructor: Lic. Tech. Petri Rönnholm

In this thesis, the uses and possibilities of the photogrammetric documentation methods in the archaeological excavation process have been examined. The theory of the photogrammetric documentation process is described and tested in the case study of Finnish Jabal Haroun Project.

The archaeological excavation is a destructive, non-repeatable and fast-paced activity. Therefore, a reliable documentation of the excavation is crucial, as the subsequent archaeological analyses are also based on it. Photogrammetric methods are suitable for the documentation of the excavation process as they are accurate, non-contacting and the acquisition of the data can be done quickly.

From the photogrammetric point of view, the documentation of the cultural heritage is a demanding task. Firstly, the documentation must be done in multi-scale as the interest of the archaeologists extends from the environment of site to the individual findings. Secondly, as the excavation proceeds, the documentation is required to be done multi-temporally. Thirdly, the objects are commonly complex and geometrically unformed and thus, the use of multi-sensor approach is often required.

As a result, experiences of the photogrammetric documentation processes and related activities in the archaeological excavations are described through the extensive case study. The data, processes, products, archive, uses and future needs are explained and compiled into a flow chart. As a one significant aspect of the photogrammetric documentation, this research gives more emphasis on the realistic and photo-textured 3D modeling.

TEKNILLINEN KORKEAKOULU   DIPLOMITYÖN TIIVISTELMÄ

Tekijä:	Hanne Junnilainen
Työn nimi:	Fotogrammetrinen dokumentointi arkeologisessa kaivausprosessissa – case: Finnish Jabal Haroun Project
Päivämäärä:	31.5.2007 **Sivumäärä:** 84

Osasto:	Maanmittausosasto
Professuuri:	Maa-57. Fotogrammetria ja kaukokartoitus
Pääaine:	Kaukokartoitus

Työn valvoja: Professori Henrik Haggrén

Työn ohjaaja: TkL Petri Rönnholm

Diplomityössä tutkitaan fotogrammetristen dokumentointimenetelmien käyttöä arkeologisessa kaivausprosessissa. Fotogrammetrisen dokumentoinnin teoria on kuvattu ja testattu Finnish Jabal Haroun –projektissa.

Arkeologinen kaivausprosessi tuhoaa kohteensa, se toteutetaan nopeasti ja sitä ei voida toistaa. Siksi kaivausprosessin dokumentointi on ensiarvoisen tärkeää. Lisäksi myöhemmin tehtävät arkeologiset analyysit perustuvat tuotettuun dokumenttiin. Fotogrammetriset dokumentointimenetelmät soveltuvat hyvin kaivausprosessissa käytettäviksi, sillä ne ovat tarkkoja menetelmiä, joissa ei tarvitse koskettaa kohdetta ja kuvat voidaan hankkia nopeasti.

Fotogrammetrisen tutkimuksen kannalta kulttuuriperinnön kohteet ovat haasteellisia. Kaivausprosessi tulee dokumentoida useassa mittakaavassa, sillä arkeologin mielenkiinto kattaa kaiken kohteen ympäristöstä yksittäisiin löytöihin. Lisäksi dokumentointi suoritetaan useana ajankohtana kaivausprosessin edetessä. Fotogrammetrisen mittaamisen kannalta tutkimukselliseksi haasteeksi nousee kohteiden monimutkaisuus ja geometrisesti selkeiden muotojen puute, mikä on johtanut erilaisten aineistojen ja instrumenttien yhteiskäyttöön.

Tuloksena on esitetty kokemukset fotogrammetrisesta dokumentointiprosessista arkeologisilla kaivauksilla laajan case-tutkimuksen kautta. Aineistot, prosessit, lopputuotteet, arkisto, tuotteiden käyttö ja tulevaisuuden näkymät on kuvattu ja koottu prosessikaavioon. Yhtenä tärkeänä fotogrammetrisen dokumentoinnin menetelmänä on painotettu realistista, fototeksturoitua 3D mallintamista.

Avainsanat: Fotogrammetrinen dokumentointi, arkeologinen kaivausprosessi, 3D mallintaminen	**Kieli:** Englanti, tiivistelmä suomeksi

Acknowledgements

TABLE OF CONTENTS

REFERENCES

LIST OF FIGURES:

LIST OF TABLES:

ABBREVIATIONS

3D	Three-dimensional
AD	Anno Domini
a.k.a.	Also known as
BC	Before Christ
DEM	Digital elevation model
e.g.	For example (exempli gratia)
FJHP	Finnish Jabal Haroun Project
GIS	Geographical Information System
i.e.	That is (id est)
f	Principal distance of the camera is the distance between the principle point and image plane.
GPS	Global Positioning System
K_1, K_2, K_3	Coefficients of the radial lens distortion
KVR-1000	Russian satellite images of the KOSMOS satellite
mgon	Milligon
NEH	UTM coordinates (Northing, Easting and Height)
O	Percpective center
(p_x, p_y)	Pixel size
P_1, P_2	Coefficients of the tangential lens distortion
RMS	Root mean square
$r_{11},....,r_{33}$	The elements of the rotation matrix $R_{\omega\varphi\kappa}$ defining the relation between image and object coordinate systems.
(x_0, y_0)	Coordinates of the principal point. It is a point in the image plane, in which the line coming from the percpective center intersects perpendicularly with the plane.
(x, y)	Image coordinates

(x, y, z)	Local geodetic topocentric coordinates
(x', y', z')	Camera coordinates
(X, Y, Z)	Object coordinates
(X_0, Y_0, Z_0)	The position of the percpective center
ω	The rotation around the x-axis
φ	The rotation around the y-axis
κ	The rotation around the z-axis

Chapter 1

Introduction

1.1 Background

Archaeology studies past human activities based on material remains, and excavations have a key role in the collection of the material. During the archaeological work, most of the archaeological site is excavated and thus destroyed, and therefore, the process is non-repeatable. Consequently, the post-excavation analysis depends completely on accurate documention of the excavation process. Additionally, the excavations are typically carried out in a fast-paced schedule, but at the same time, the documentation of each excavated layer is time consuming.

Photogrammetry is a discipline in which imagery is used for measuring and modeling the object three dimensionally (3D). Photogrammetric methods are suitable for the documentation of the excavation process as they are accurate, capable for detailed 3D documentation, non-contacting, cost-effective, and the acquisition of data can be done quickly. As an important characteristic of the photogrammetry, the obtained image data is non-interpreted and the texture can be attained. Photogrammetry also enables the collection of large amount of data with various scales and resolutions, the procedures are typically monitored to ensure the quality and the data can be geo-referenced. The stereo viewing capability also facilitates the archaeological interpretations. (Patias, 2006.)

1

From the photogrammetric point of view, the documentation of the cultural heritage is a demanding task. Firstly, the documentation must be done on multi-scale as the interest of the archaeologists extends from the environment of site to the site itself, its individual trenches and findings (Fig. 1). As the quality and resolution are varying through one documentation case, also the desired level of details and their implementation need to be specified carefully. Secondly, the documentation is required to be done multi-temporally as the excavation proceeds. Thirdly, the objects are commonly complex and geometrically unformed, and therefore, diverse data and multi-sensor approaches are required in many cases. In fact, the complexity of each site makes it unique and that way all the specificities are meaningful (D'Ayala and Smars, 2003).

Above all, the photogrammetric documentation in archaeology is not only seen as a way to produce the end products of all the data collected, but also as a photo archive, which can later be used for the information retrieval even with the new research questions in mind. For this use, the value of the image data lies in its non-interpreted characteristic. On the other hand, in order to appropriately fullfill the future needs, careful attention should be put on the acquisition process of the data, as the recording must be complete.

However, the documentation of the cultural heritage is not an end in itself; the aim of the documentation is to make data available to other users (Patias, 2006). Böhler (2006) has specified different reasons for the sharing of information: when the object is not accessible; the objects are too large and complicated to be seen at once; when the object is only visible for a short period of time; when the object is too far to be visited; and when the object is in danger to be destroyed or degenerated.

The importance of the cultural heritage documentation has been recognized both nationally and internationally. Accordingly, international organisations have created guidelines describing standards and specifications of the documentation. The International Council on Monuments and Sites (ICOMOS) and UNESCO's International Charter for the Conservation and Restoration of Monuments and Sites (1964) emphasize recording of large amount of accurate and factual data; the demands of 4D (3D and time), multi-source, multi-format and multi-content data;

2
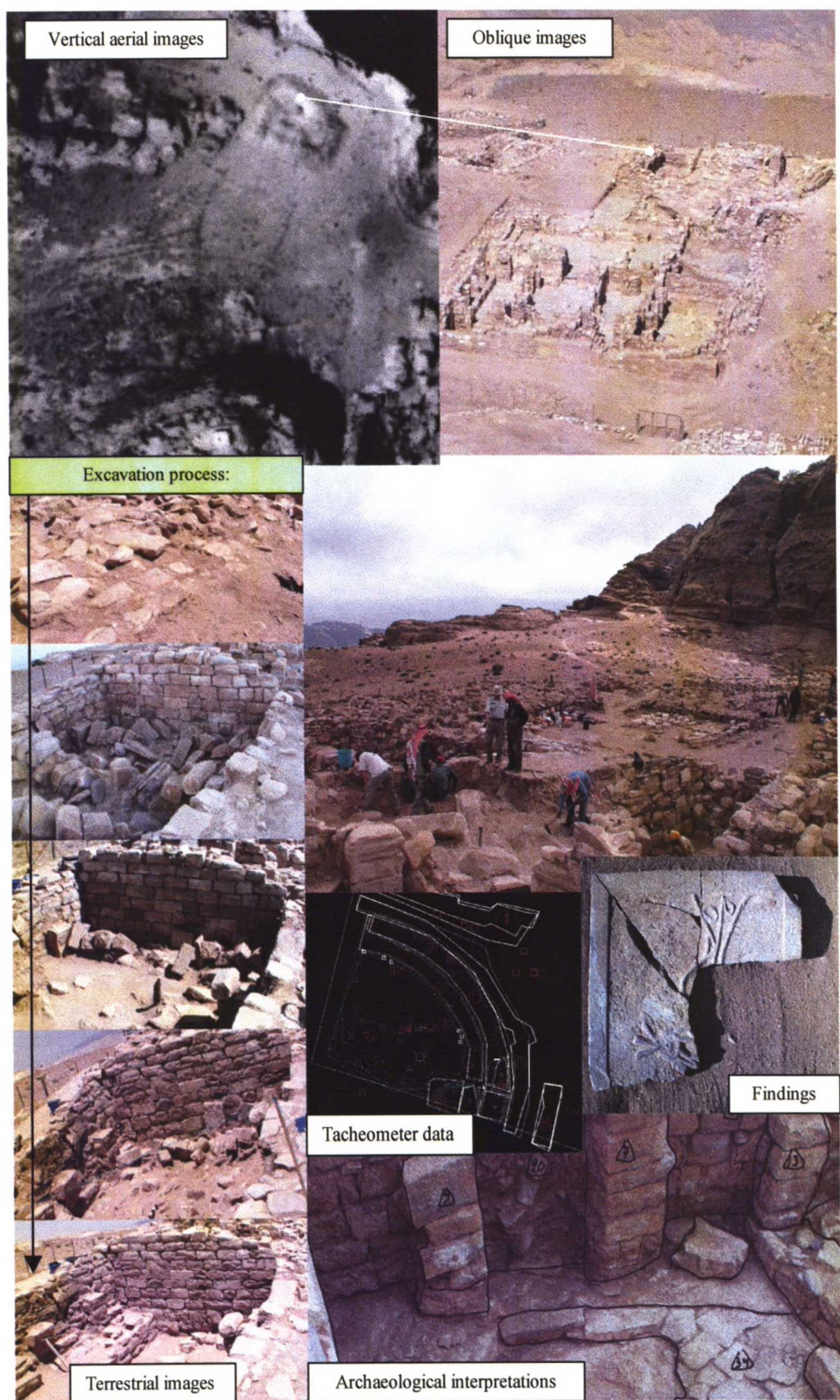
Figure 1. Multi-scale, multi-sensor and multi-temporal data used in the documentation of the archaeological excavation process in FJHP.

digital inventories based on historical images; management of the 4D data to increase availability of the data; and visualizations which are easy to interpreted and can be presented through Internet (ICOMOS Charters, 2007). As a collaboration between ICOMOS and International Society of Photogrammetry and Remote Sensing (ISPRS), "the International Committee for Heritage Documentation" (CIPA) was established in 1969. CIPA has provided an international forum for improving photogrammetric and surveying methods in the recording, monitoring, preservation and restoration of monuments and sites (CIPA, 2007). (Patias, 2006.)

1.2 Past and Current Research

Photogrammetric documentation has been used in archaeology since the 19th century. The ancient ruins of Persepolis were perhaps the first archaeological objects recorded by photogrammetry (Stolze, 1883). Thereafter, photogrammetric techniques have been constantly evolving (Konecny, 1985; Atkinson, 1996; Mikhail et al., 2001) and their use in cultural heritage has been manifold (Patias, 2006). In recent years, the development from optical-mechanical to digital hardware and from expensive to low-cost software has considerably advanced the operative uses of photogrammetry. At the same time, the uses of new methods in the documentation of the cultural heritage have been increasing: e.g. panoramic imaging (e.g. Haggrén et al., 2004b; Salemi et al., 2005; Luhmann and Tecklenburg, 2005; Reulke et al., 2006); monoplotting (e.g. Karras et al., 1996; Gaisecker, 2006); true orthophoto production (e.g. Georgiadis et al., 2000; Ioannidis et al., 2001; Tsiligiris et al., 2003; Balletti et al., 2005); fusion of photogrammetric data with data from other sensors (e.g. Lingua et al., 2003; Balletti et al., 2004; Guarnieri et al., 2004; Haala and Alshawabkeh, 2006); and laser scanning (e.g. Bernardini et al., 2002; Tsioukas et al., 2004; Böhler, 2006; Vico et al., 2006; La Pensée et al., 2006). Besides the terrestrial photogrammetry, aerial archaeology – the use of aerial images in the archaeological survey and documentation – has roots in the beginning of the 20th century and has been popular e.g. in the Great Britain. Variety of platforms ranging from balloons to satellite images has been used, but in general, aerial photography has been the most conventional technique to reveal archaeological features from the air (Wilson, 2000).

4

As a signicant task of the photogrammetric documentation – 3D modeling has been applied to various tasks in archaeology and cultural heritage. Applications has ranged from the documentation of buildings (e.g. Liebowitz *et al.*, 1999; Dick *et al.*, 2000; Gonzo *et al.*, 2004) and statues (e.g. Visnovcova *et al.*, 2001; Gruen *et al.*, 2004) to the reconstruction of small archaeological artefacts (e.g. Gemenetzis, 2001; Bujakiewicz *et al.*, 2006; Verbiest *et al.*, 2006) and large environments (e.g. Lianos *et al.*, 2004; Reindel and Gruen, 2006; Gruen *et al.*, 2006; Vergauwen *et al.*, 2006). In the modeling of complex or large sites, particularly the multi-sensor approaches have been increasing (e.g. Allen *et al.*, 2003; Tucci *et al.*, 2003; Aguilera *et al.*, 2006). Nevertheless, only a small the amount of publications can be found dedicated to the documentation of the excavation process (Pollefeys *et al.*, 2000; Pateraki *et al.*, 2002; Ullrich *et al.*, 2003; Doneus and Neubauer, 2005).

1.3 The Aim of the Study

The study is done as a part of Finnish Jabal Haroun Project (FJHP). The extensive case study has a significant role in this thesis and thus, the aims of the study follow the general photogrammetric objectives of the project (See Chapter 4.4.).

The first aim of this thesis is to document the experiences and observations of the photogrammetric documentation obtained during the fieldwork. A specific objective is to compile the photogrammetric processes and related activities into one description and a workflow. It is also important to understand the relations and supplementary nature of the different methods.

The second aim is to facilitate the creation of the virtual geographic model (See Chapter 4.4.). Therefore, the procedure to built realistic and photo-textured 3D models of the excavation process is examined and tested. From the archaeological point of view, the 3D modeling aims to document the archaeological excavation, visualize and document the process of the excavation, and support archaeologist in their analyses.

1.4 Organization of the Thesis

Chapter 2 goes briefly through the science of archaeology, archaeological excavation process and its documentation. Chapter 3 is dedicated to the theoretical aspects of photogrammetric documentation process. The case study of the photogrammetric documentation in archaeological excavation process in Finnish Jabal Haroun Project is described in Chapter 4. The practical aspects of the photogrammetric documentation in the excavations are discussed in the Chapter 5. Finally, conclusion are presented in Chapter 6.

Chapter 2

Archaeological Excavation

2.1 Archaeology

The aim of the archaeology is to systematically study past human life and cultures by analysing remaining material evidence. Archaeology also attempts to formulate explanations for the development of cultures. As the material evidence has the main role in the examination, most of the material is collected by excavations. The first scientific *archaeological excavation* was conducted in the 18th century, but it was not until middle of the 19th century that the discipline of archaeology was actually established. The development of the discipline has later broadened to spatial aspects, such as studying material in the finding context of the entire landscape. *Archaeological survey* searches for new archaeological sites and creates documents of previously discovered sites based on evidence observed on the surface.

Archaeology is at the same time a human and historical discipline. Whereas a cultural anthropologist base their outcomes on the experience of living within existing societies, archaeologists study the buildings, tools and artefacts remaining from the former societies. While a historian concentrates on the historical time and written evidence, an archaeologists studies all cultures and periods with or without written sources.

In the respect of the material study, the archaeology also resembles a natural science. The archaeologist collects the evidence, carry out experimentation, formulates hypothesis, tests the hypothesis, and as a conclusion, formulates a model – an explanation that seems to fit to the pattern observed in the data. On the other hand, archaeology is a human science since interpretations and conclusion are derived from the raw archaeological material. In fact, the most demanding task for the archaeologist is to find explanations of the material culture – how was that material used?

The traditional division of the science of archaeology is done by the chronology: pre-historical (e.g. Mesolithic and Palaeolithic) and historical periods (e.g. Egyptology and Classical Archaeology). Later, development of the discipline has brought along new needs and sub-divisions. Environmental archaeology studies the human use of plants and animals and how former cultures adapted to the changing environments. An underwater archaeologist researches past human activities both on the sea and on the land. Ethnoarchaeologist studies how contemporary communities use materials and by this means, attempts to comprehend the formation processes of the archaeological record. Social archaeology, on the other hand, examines the social organization and the changes of the past societies. Cognitive archaeology is one of the latest branches of the contemporary archaeology – it studies past ways of thinking based on material remains.

(Renfrew and Bahn, 1996.)

2.2 Excavation Process

The only method to test the reliability of surface data and actually to see the remains of the site is to excavate (Fig. 2). Excavation maintains its important role in the archaeological work as it offers the most reliable source for the two main type of information archaeologists are interested in: past human activities in the specific time period and changes in the activities through time. (Renfrew and Bahn, 1996: 97-100.)
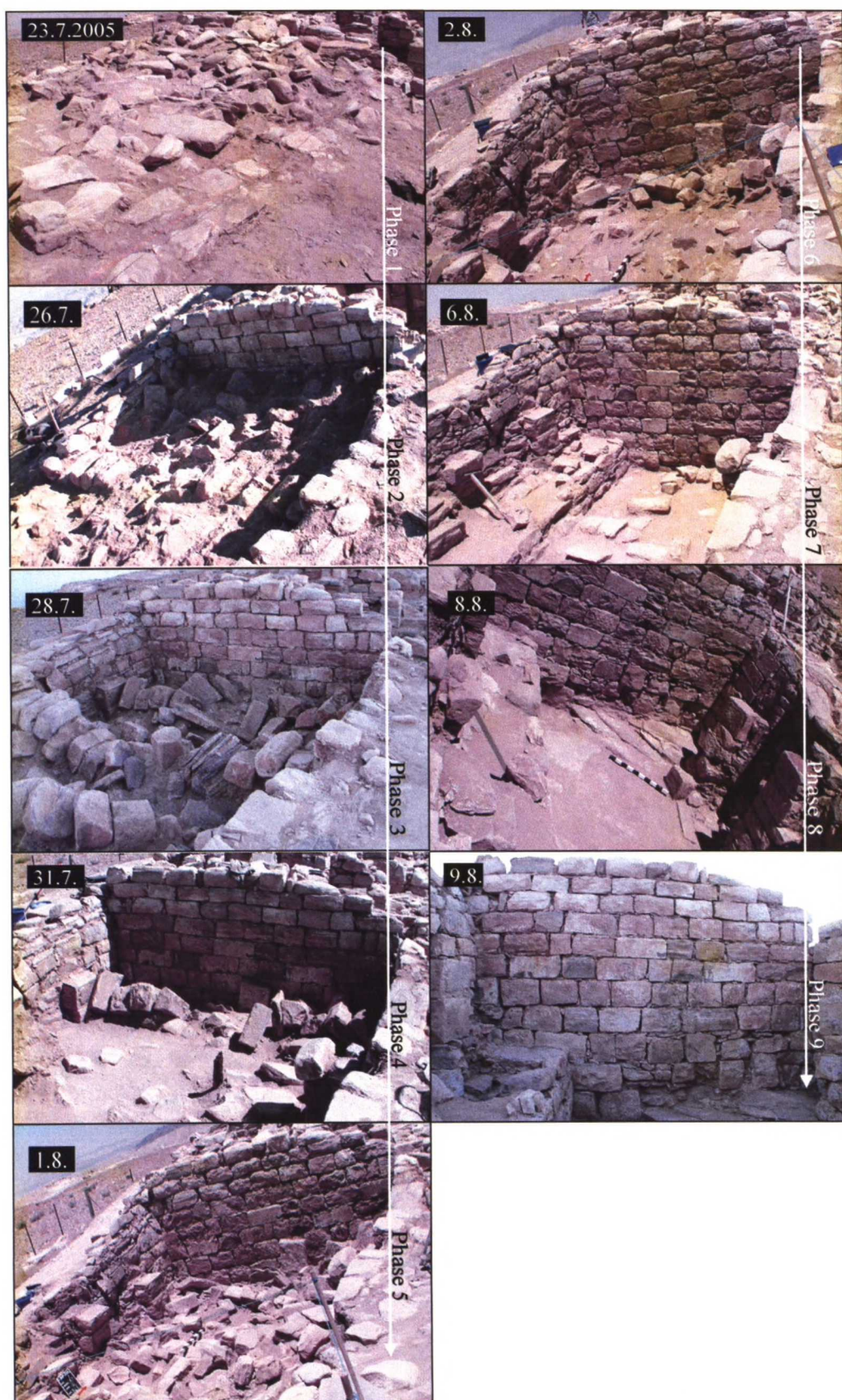
Figure 2. The progress of the excavation photographed in trench A1 (app. 4 x 6 meters) in FJHP. As it can be seen from the progress of the digging, the excavation process is a fast-paced and destructive activity. Also the changing lightning conditions and strong contrasts can be noticed.

In the understanding of the excavation process, the *stratigraphy* has a key role. In the stratification process, layers or strata are laid down on top of the other, as a still continuing process (Fig. 3). In the case of the archaeology, the strata is the layers of cultural or natural debris. As another important conception, *law of superposition* states that where one layer overlies another the lower layer was deposit first. Therefore, a succession of layers should provide a relative chronological sequence from the earliest (bottom) to the latest (top). Above all, the stratification of every archaeological site is unique (Harris, 1989). Therefore, description and interpretation of the stratification has the key role in analysis of the excavated material. As a result, the main objective of the excavation process is to document the stratification as completely as possible. (Doneaus *et al.*, 2003; Renfrew and Bahn, 1996: 97- 100.)
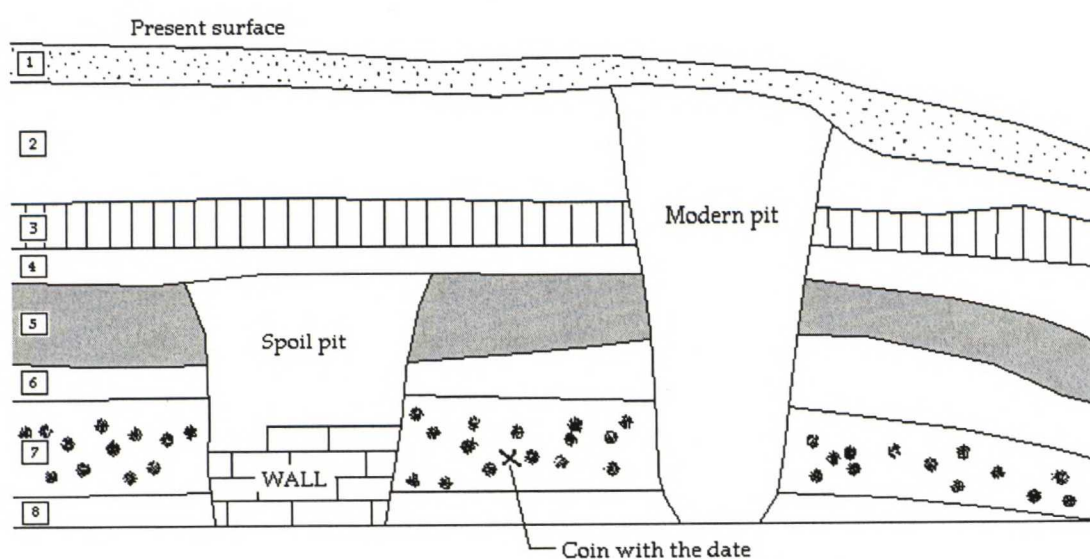
Figure 3. Imaginary stratification of an excavation trench. Stratigraphical units are presented with a number. (Adopted from Renfrew and Bahn, 1996)

Excavation method has to be adjusted according to the research question, characteristics of the site and resources. Generally speaking, one can divide excavation techniques into two categories: those that try to reveal vertical, stratigraphical layers by excavating in a trench-system, and methods that emphasize the broader horizontal dimension to reveal spatial relationships between artefacts and features of the layer in question. Most excavations use a combination of both strategies, and no single method can universally be applied in all excavation types. In particular, since the excavation destructs most of the evidence and it is an unrepeatable exercise, the excavation method is as good as its methods of recovery and recording. In the case of FJHP, mainly the trench-based stratigraphical

10

excavation method is applied and therefore, this thesis concentrates on its documentation (Fig. 4). The stratigraphic excavation method, as defined by Harris (1989), enables to document the single unit of stratification along with all its attributes and relations to *stratigraphic sequence*. (Renfrew and Bahn, 1996: 100-103; Burke and Smith, 2004: 123.)
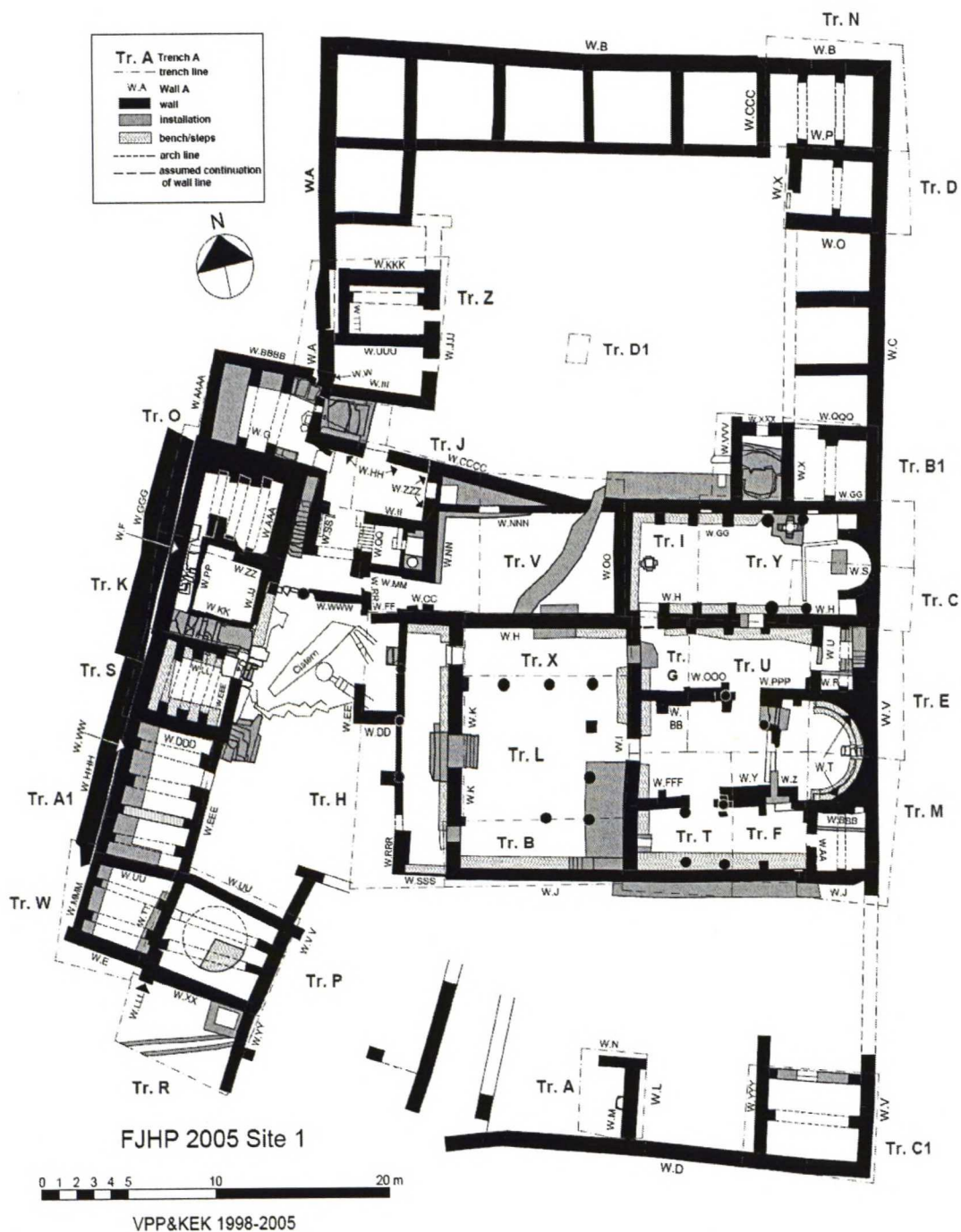
Figure 4. Top plan of the FJHP excavations 1998-2005. In FJHP, stratigraphic excavation method is mainly used. To reviel the vertical dimension of the site, it has been divided into trenches (A, B,..., C1). The trenches are further divided into locuses a.k.a. stratigraphical units. (FJHP/Katri Koistinen ja Vesa Putkonen)

11

In practice, stratification of the archaeological excavation comprises of discrete archaeological entities a.k.a. layer, locus or stratigraphical unit. Units are defined according to the natural archaeological deposits (e.g. earth layer, wall, pit, ditch and fire place) and therefore, they describe use and periods of a site. Starting from the surface, deposits are removed in the reverse order compared to the order they were formed. In a site, there are often also several levels of ruins since the site might have been constructed upon other site. On the other hand, archaeologists are also interested on the surrounding environment, since it can reveal what may have happened at a site. (Doneaus *et al.,* 2003; Renfrew and Bahn, 1996; Burke and Smith, 2004.)

2.3 Documentation of the Excavation Process

As already emphasized, the an excavation is as good as its documentation. Since the most of the archaeological site is excavated and thus destroyed, the post-excavation analysis and layer-by-layer reconstruction of the site depend completely on precise records of the excavation process.

Every stratigraphical unit is formed by material *(deposit)* and immaterial *(surfaces or interfaces)* characteristic. Deposits can only be documented partially, since most of their mass is simply removed by excavators. In a typical stratigraphical excavation, only small part of the finds can accurately be located when discovered. Part of the excavated mass is sampled and finds, recovered by sampling, can be connected to the corresponding strata. On the other hand, the surfaces can be documented completely and therefore, they are in significant role in the documentation process. This is also reasonable from the archaeological point of view, since the surfaces account far more time in the history of site than the deposits do. (Doneus *et al.,* 2003.)

Traditionally, the progress of the excavation is documented in a notebook or/and data sheets (Fig. 5). After an artefact has been found, its location is recorded, an identification number is given and it is entered into a catalog book. Before storing, a fundamental archaeological practice of cleaning and classification of the artefacts is

performed. Unlike artefacts, features and deposits need to be removed or left in situ. They have traditionally been documented with descriptive information, dimensional drawings and photography. Also the use of tacheometer has been increasing. (Renfrew and Bahn, 1996: 104-105.)

Figure 5. An archaeologist documenting the excavation process into his notebook and data sheets. (FJHP)

In some excavations, the recording is still done in 2D, but nowadays the use of 3D approaches is more common. The 3D recording is particularly important in the stratigraphical excavations – as the vertically varying deposits need to be related together into a sequence – and therefore, is also used in FJHP. From our perspective, following features of the one stratigraphic unit need to be documented in order to reconstruct the layer adequately:

- Interfaces of the deposit in 3D: boundary polygon and the topography of the surface.
- Connections between the stratigraphical units.
- 3D locations of the findings
- 3D location of the samples (volume)
- Other information and observations in relation to the stratigraphical units.

As a next step, *stratigraphic sequence* can be created by merging single stratigraphical units together based on spatial relationships. Sequences can be used for visualization of time and as a model for archaeological analysis. The total record – descriptive information, geometrically correct 3D document, interpreted drawings, photographs and artefacts – will be used in the post-excavation analysis, which can take months or years. Also the conservation process of the structures and artefacts is a significant task. (Doneaus *et al.*, 2003; Renfrew and Bahn, 1996.)

Chapter 3

Photogrammetric Documentation Process

Photogrammetric documentation process aims to reconstruct a geometrically interpreted 3D model of an object. The process is a chain of operations based on photographs or optical sensor data and can be presented as follows: 1) calibration of the camera, 2) definition and pointing of the coordinate system, 3) image acquisition, 4) orientations of the acquired images, and 5) 3D interpretation and measurements of the object. From the photogrammetric point of view, the focus of the process is in the image orientations. One could consider the reconstruction to be an inverse process compared to the image formation. (Schenk, 1999; Haggrén, 2001.)

In this thesis, the theories of the camera calibration, image acquisition and orientations are described. Definition and pointing of the outer coordinate system is represented through the case study. The 3D interpretation and measurements of the object are done manually in this study, so the theories concerning the automation of the procedure are only briefly mentioned in the Chapter 4.

3.1 Camera Calibration

In a broad sense, the camera calibration can include the geometric calibration, image quality evaluation and radiometric calibration. With images to be used for

measurements, the geometrical calibration is the main task and is discussed in this chapter. (Mikhail *et al.*, 2001: 67-71.)

The aim of the geometric camera calibration is to mathematically model what happens to the bundle of rays when coming from the target and passing through the lens system of the camera. The ideal mathematical model of the phenomenon is the central projection, but it does not represent the reality completely – also the distortions caused by the camera need to be considered. (Cooper and Robson, 1996.)

Typically, the coordinates of the principal point, the principal distance and the geometric parameters of the lens system are defined in the geometric calibration. Subsequently, these are used in the interior orientation to define the coordinate transformation from the image to camera coordinates and to compensate the distortions on the images. (Cooper and Robson, 1996.)

In the case of digital cameras used in the close-range application, the aberrations in the ideal model are mainly caused by the changes in the camera body and geometrical distortions of the lens system. The changes in the camera body are non-systematic and therefore, the digital camera needs to be calibrated regularly. Conversely, the geometrical distortions are typically systematic. They are defined during the camera calibration and can be used as additional parameters in the interior orientation. Mathematical models of the lens distortions are further discussed with the interior orientation in the Chapter 3.3.1.2. (Schenk, 1999; Atkinson, 1996.)

The development of the methods used for the camera calibration in the close-range applications has been significant. In many close-range cases, the calibration must also be time and cost-effective solution or even to be done in real-time. In the past, expensive calibration instruments or test ranges with the accurately known targets were necessary. Nowadays, calibration can be performed without known coordinates of the targets or the camera stations, and the time used for the calibration has declined notably. The low-cost computers and calibration software has enabled the techniques of on-the-job calibration and self-calibration to be commonly used. (Fryer, 1996: 164-165.)

The collinearity equations (formula 6) or direct linear transformation (DLT) are usually used for the calculation of the camera parameters. Camera calibration can be performed as a separate procedure or as a part of bundle block adjustment (self-calibration). If the calibration is done separately, the parameters of the interior orientation are fixed in the block adjustment. (Atkinson, 1996.)

On-the-job calibration can be done at the same time as the photography of the object is acquired. Then, the calibration frame with the targets can be photographed simultaneously with the object. This is particularly useful in the cases where the each photograph need to be taken with certain zoom or aperture. (Fryer, 1996: 166.)

In the self-calibration, the object point calculation and determination of the camera parameters are done simultaneously. The solution is calculated in the bundle block adjustment by adding parameters for lens distortions to the collinearity equations (Mikhail *et al.,* 2001: 124-125). The principal point coordinates and principal distance appear directly in the equations. Known control points can be used to define outer orientation, but they are not necessary for the camera calibration. However, attention needs to be put on the imaging geometry, as multiply images taken with strongly convergent configuration are required and several images need to taken from each camera station by rotating the camera e.g. 90 degrees. Additionally, targets should be seen from multiply camera stations and they are required to be spread across the entire image format area. Instead of planar arrangement, it is also preferably to construct 3D configuration of the targets. Consequently, the self-calibration should only be used with the certain cases where the imaging geometry is strong enough and the object is geometrically formed. The parameters to be used should also be chosen carefully. However, the self-calibration is particularly practical in situations in which parameters are needed to be defined under operational conditions. Anyhow, the accuracy of the object coordinates is the main concern of a photogrammetrist – not the camera calibration techniques. (Fryer, 1996: 166-168, 174.)

3.2 Image Acquisition

Image acquisition has a fundamental importance in the photogrammetric documentation process. Image acquisition determines the level of completeness and details of a document, as well its accuracy and reliability. In this chapter, ideas of panorama, stereo and convergent photography are reviewed. Furthermore, the camera network design has specially been addressed.

3.2.1 Panorama Photography

A panorama image is usually a horizontally wide image. It imitates the human vision; we have eyes side by side and the head can be turned horizontally in a way that we can easily see 360 degrees. Consequently, brain perceives the panorama images without difficulty. Nowadays, also vertically spreading, spherical panoramic images are produced (Kukko, 2001). (Nuikka, 2002.)

Panorama photography can be acquired by wide-angle cameras; panorama cameras, which has rotating lens system or frame; or with the normal frame cameras by rotating the camera and combining the images afterwards. Additionally, special objectives, e.g. fish-eye lens, can be employed. (Nuikka, 2002.)

In the case of FJHP, panorama photographs have been generated by combining two or more normal digital images (Fig. 6). Petteri Pöntinen (2000) developed in his licentiate's thesis the theoretic method for creating horizontal panoramic images from image sequences without external control data, such as control points in the field or known angles of rotation during image acquisition. The mechanical cross-slide mount (Fig. 19) is used during the photography in order to ensure that perspective centre remains stable while rotating the camera. (Junnilainen *et al.*, 2007.)

The images in the sequence have to be acquired with an overlap of 30 to 50 %. With the help of corresponding points or features, all images can be rectified into a common plane or cylinder. The rectification to a plane is done by projective transformation (Wong, 1980: 50), and during the rectification, optical lens

18

distortions are compensated. Thus, the image can be used for photogrammetric measurements. The practical usefulness for photogrammetric application is due to the fact that panoramic photography produces wide-angle and high-resolution images. (Haggrén *et al.*, 2004a; Junnilainen *et al.*, 2007.)
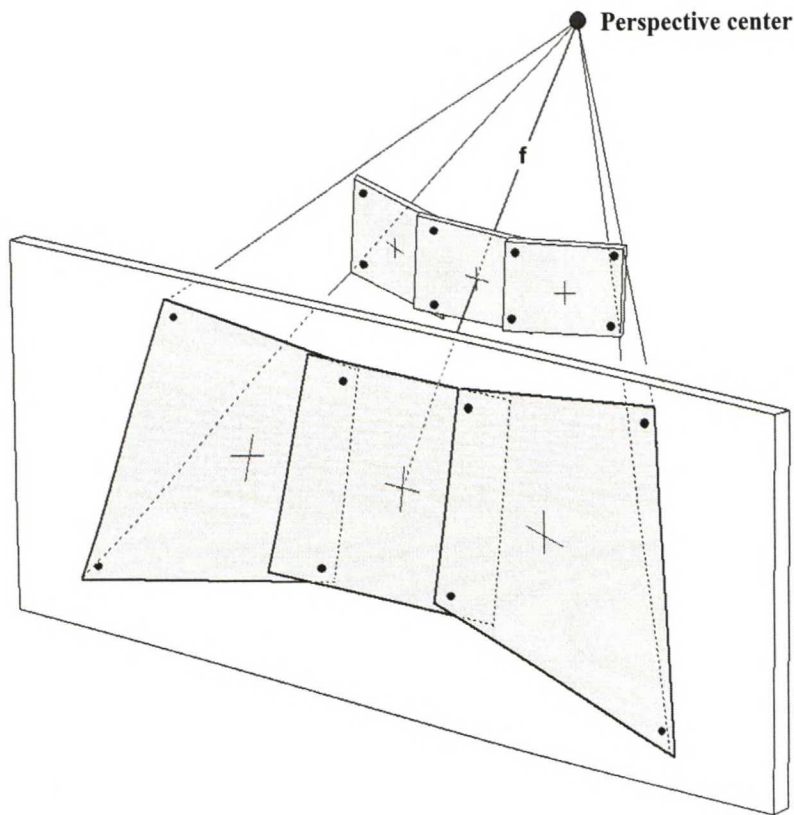
Figure 6. The principle of the panoramic photography. Images are taken without moving the percpective center and are projected to a common plane by 2D projective transformation. (Adopted from Haggrén *et al.*, 2004a)

3.2.2 Stereo Photography

Stereo photographs mimic the binocular vision of the human – the 3D system of two eyes. Correspondingly, the depths of imagery can be perceived if the right and left eyes have own images to be observed. This is based on the ability of brain to translate the horizontal image parallaxes into the feeling of the depth (Fig. 7). The larger parallax will make the point seem to be nearer to the observer than the point that has smaller parallax. Based on the same idea, the 3D world can be reconstructed from the stereo images. (Mikhail *et al.*, 2001: 27.)
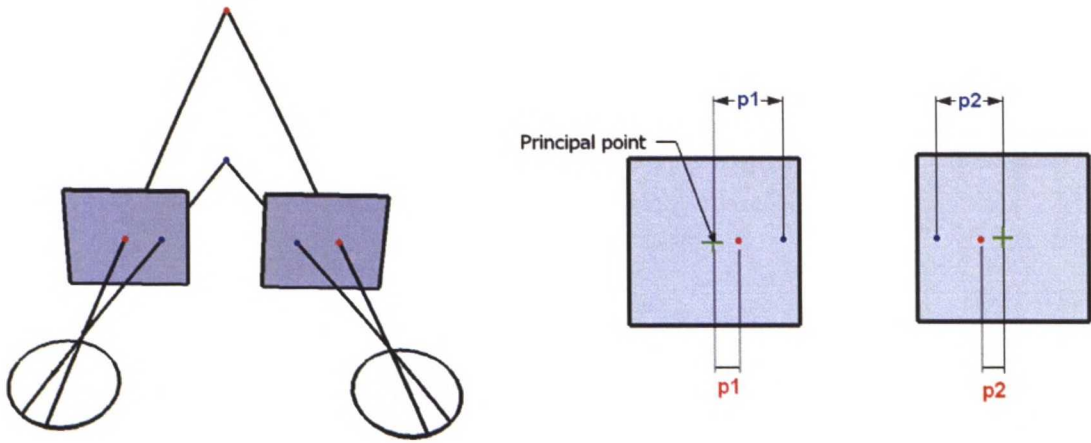
Figure 7. Stereo vision. Parallaxes are measured by adding absolute values of p1 and p2 of a point. The point with the larger parallax will make the point seem to be nearer.

The stereo photographs can be obtained by stereo or ordinary cameras. Stereo cameras have two lenses in an eye-distance apart. With an ordinary camera, stereo photographs are acquired by taking two images with a certain base-to-distance ratio (Ferwerda, 1987). In the normal case of the stereo photography, two images are taken from two slightly different perspectives, but parallel to each other (Fig. 8). The shift, which is called the base-line, has to remain orthogonal, i.e. normal to the viewing direction. In order to cover the target without shadows in the stereo view, the base-line should remain short. A good rule-of-thumb has been to keep the length of the base short, i.e. less than about 1/20th of the distance to the object. It is also important to keep the vertical level constant when shifting the camera, as the difference in level will rotate the horizon in the stereo view. The parallax is relative to the base – the depth impression can be exaggerated by increasing the base. (Junnilainen *et al.*, 2007.)

The normal case of stereo imaging allows simple production of stereo views (Ferwerda, 1987: 25-28). Stereo images can be presented with polarization, LCD shutter, autostereoscopy, anaglyph or separate image techniques. Here, the techniques of anaglyphic prints and separate images are reviewed. In anaglyphic presentation, the left-right image separation is facilitated by complementary colors. The stereo print is recomposed e.g. by combining the red color from the left image and the cyan color from the right image. For viewing, one needs anaglyphic glasses with respective red and cyan filters. (Junnilainen *et al.*, 2007.)

20
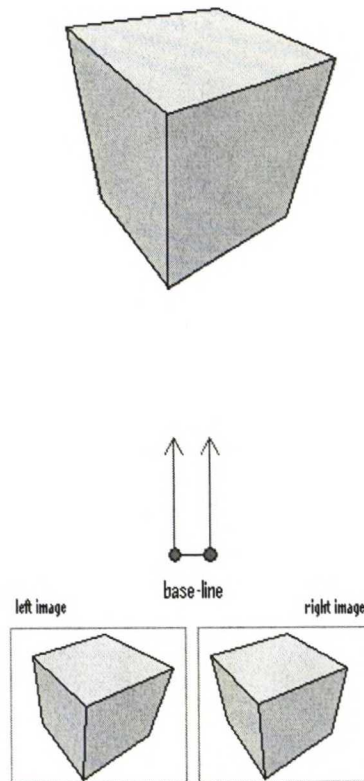
Figure 8. Normal case of stereo photography. In order to facilitate convenient stereo viewing, the base-line should be kept short and the photographs should be taken parallel to each other. (FJHP/Henrik Haggrén)

The left-right image separation can also be done by viewing the original image separately. Then the images can be viewed without any additional accessory, either by parallel or crossed viewing direction (Ferwerda, 1987: 32-39). Crossed viewing is physically more convenient as eyes naturally converge while aiming at a target. Then, the images are printed next to each other in the opposite order, the original right image to the left and the original left image to the right. (Junnilainen *et al.*, 2007.)

3.2.3 Convergent Photography

The convergent photography consists of several images taken from all sides of a target towards its center (Fig. 9). Images are not overlapping in a specific manner like in the stereo case, but the imaging rays converge at the object. The method is generally accepted to be more accurate than stereoscopic measuring. The systems using convergent and multi-image configuration are nowadays obtaining accuracies of 1:100 000 (Fraser 1996: 256), but careful consideration to the camera network

21

design need to be addressed then. As the photographs can be taken from all sides and distances of an object, the method is suitable for the 3D modeling and complex targets in which several images need to be taken to cover it completely.
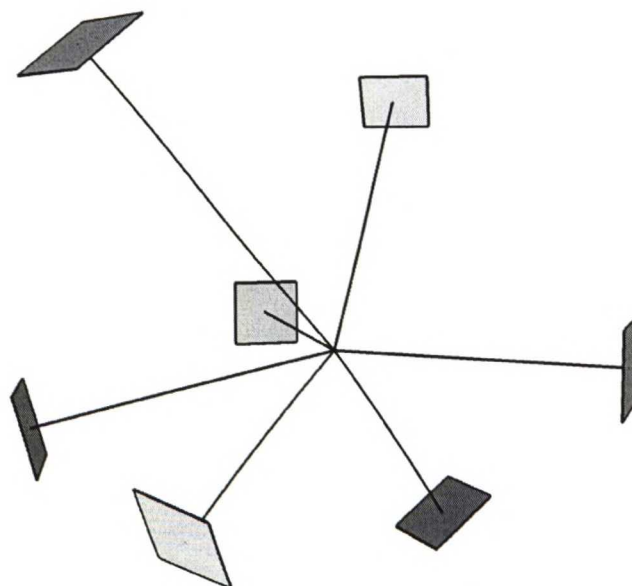
Figure 9. The principle of the convergent photography. Imaging rays converge at the target.

3.2.4 Camera Network Design

Camera network design has a fundamental importance in the photogrammetric documentation process. It is one of the main factors influencing on the accuracy and the reliability of the reconstruction (Fraser, 1996: 256-257). Besides its importance, network design is also a challenging task. Fraser (1996: 260) and Mason (1995) present a helpful simplification of network design: 'generic network'. It can be thought as an approximation of an optimal sensor configuration for a particular object shape. A suitable generic four-station configuration for measuring near planar objects is presented on figure 10. In the case of more complex targets, the design problem can be treated in two parts: generic networks are established for suitable sub-targets and then extra camera stations are added to tie these sub-networks together with sufficient geometric strength (Fraser, 1996: 264). Also Waldhäusl and Ogleby (1994) present helpful rules for photogrammetric image acquisition.
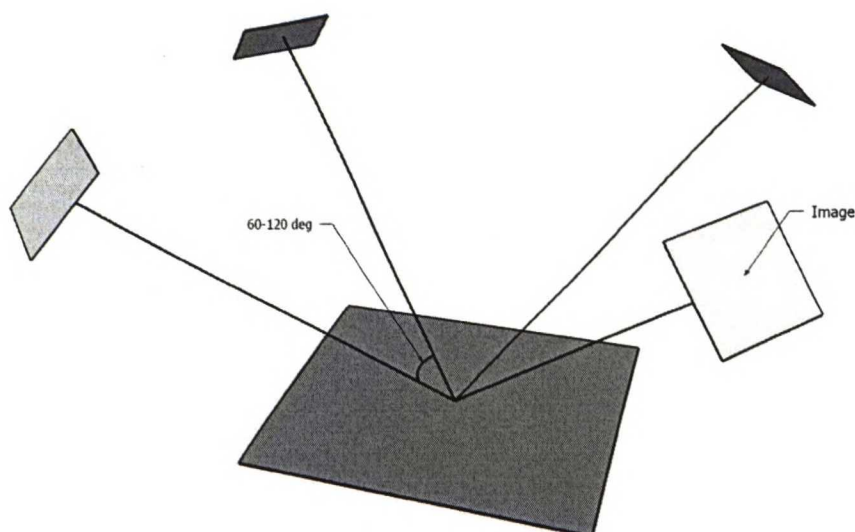
Figure 10. A suitable generic four-station configuration for measuring near planar object.

However, the 'generic network' is only a simplified idea of the optimal image acquisition. Consequently, a number of interdependent and competing constraints must be considered during the acquisition: image scale; resolution of an object in the image; workplace constraints, e.g. obstructions; depth of field; incidence angle; number and distribution of image points; intersection angles; field of view; and visibility (Fraser, 1996: 263-264).

3.3 Image orientations

Image orientations define the relation between an image and the object. Thus, coordinate transformations from the object to the images and further from the images to a 3D model need to be determined. After this chain of orientations, three-dimensional global coordinates can be calculated for each image point and camera position. (Mikhail *et al.*, 2001: 88-91 and 114-123.)

3.3.1 Interior Orientation

The geometric parameters of the camera are defined in the camera calibration and during the interior orientation, they are used to define internal geometry of the camera and to compensate the distortions on the images. (Fryer, 1996: 156-157.)

Typically, the mathematical model used in the interior orientation is the central projection. During the interior orientation, the location of the perceptive center of the camera is defined in relation to the image plane – the coordinate transformation from the image coordinates to camera coordinates is performed (Fig. 11). The used parameters are at least the principal distance (f) and the location of the principal point (x_0, y_0) on the image plane. However, the mathematical model of the central projection does not represent the reality completely; also the distortions caused by the camera need to taken in account by using additional parameters. (Kraus, 1993; Mikhail *et al.*, 2001.)
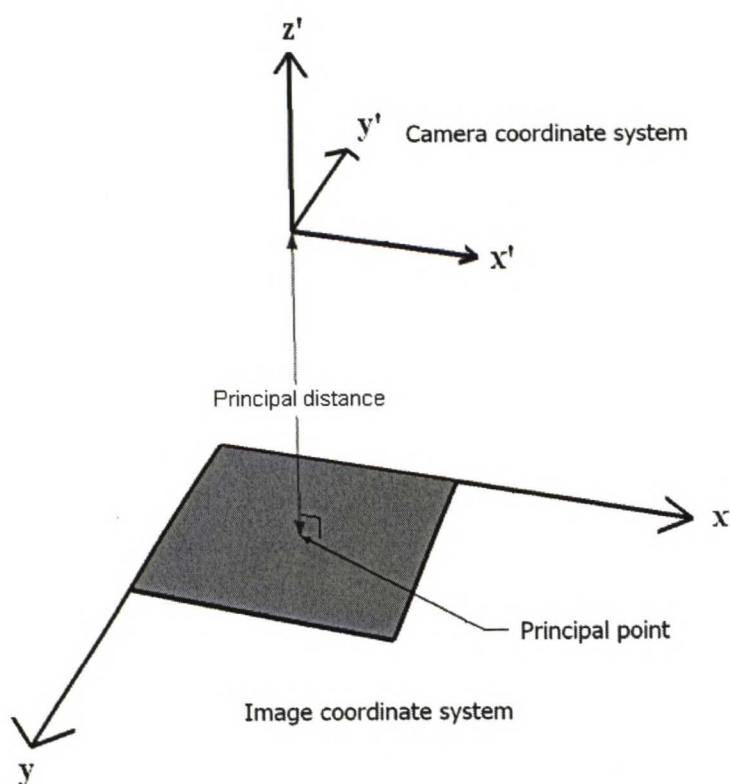
Figure 11. The relation between the 2D image coordinates and 3D camera coordinates.

3.3.1.1 Coordinate Transformation for Digital Images

The coordinate transformation from the 2D image coordinates to the 3D camera coordinates is:

$$x' = (x - x_0)p_x$$
$$y' = -(y - y_0)p_y \qquad (1)$$
$$z' = -f$$

24

(x_0, y_0) = The location of the principal point in the image coordinates in pixels

(x, y) = The image coordinates of the point to be transformed in pixels

(x', y', z') = The camera coordinates of the point to be transformed

(p_x, p_y) = The pixel size in metric units

f = Principal distance

In the case of digital camera, the principal point and the location of the principal point are acquired during the camera calibration.

(Schenk, 1999: 321.)

3.3.1.2 Additional Parameters: Distortions Caused by the Lens Distortions

The geometrical lens distortions originate from the inaccuracies happened during the grinding and installation of the lenses and differences in the refraction characteristic of each lens in the system. Distortions are comprehended as deviations in the distances measured from the optical axis compared to the ideal model of the central projection. *Radial distortion* is same in any angle at the same distance measured from the principal point, and is moving the image point towards or away from the principal point. *Decentring distortion* is symmetrical in relative to the diagonal going through the principal point and can be tangential or radial in its nature. (Fig. 12) Whereas the radial distortion develops because the individual lenses are not symmetrical, the decentring distortion is caused by the movements or rotations of the lenses around the optical axis during the installation. (Atkinson, 1996; Schwidefsky and Ackermann, 1976; Haggrén, 2002.)
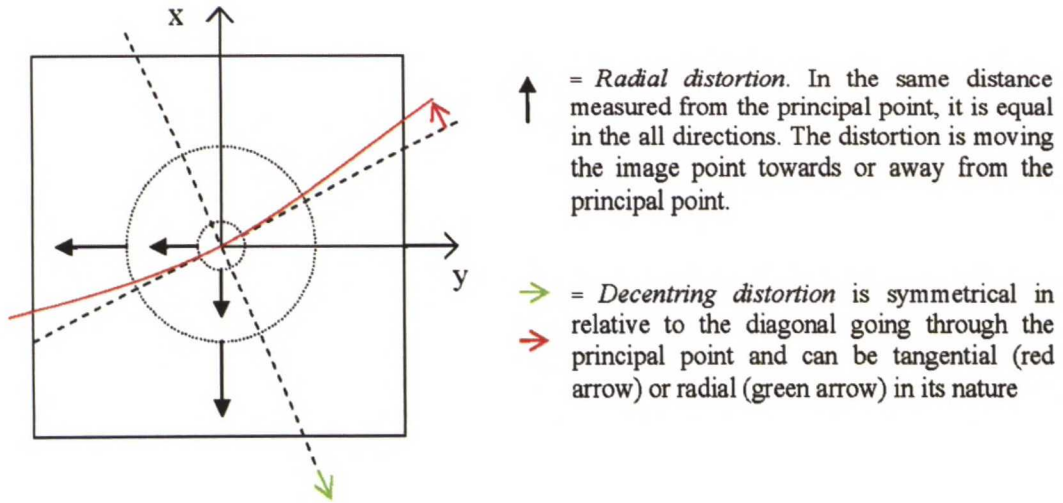
Figure 12. Radial and decentring lens distortions.

The radial distortion is commonly presented as polynomial function, which is defining the radial transition of the image point in relation to the principal point (δr):

$$\delta r = K_1 r^3 + K_2 r^5 + K_3 r^7 \tag{2}$$

$r^2 = (x-x_0)^2 + (y-y_0)^2$ = the transition of the point

(x, y) = the coordinates of the image point

(x_0, y_0) = the coordinates of the principal point

K_1, K_2, K_3 = coefficient which depends on the focal length and focus

δr is usually solved in two components in the function of x and y:

$$\delta r_x = \delta r(x-x_0)/r \tag{3}$$

$$\delta r_y = \delta r(y-y_0)/r$$

The radial distortion is growing polynomially towards the edge of the image, and it can easily grow over 50 pixels with consumer-grade digital cameras.

The decentring distortion is described by the two polynomial function in relative to x and y axes:

$$\delta x = P_1[r^2 + 2(x-x_0)^2] + 2P_2(x-x_0)(y-y_0) \tag{4}$$

$$\delta y = P_2[r^2 + 2(y-y_0)^2] + 2P_1(x-x_0)(y-y_0) \tag{5}$$

26

P_1, P_2 = coefficient which depends on focal length and focus

Other terms are same as in the formula 3.

The influence of the decentring distortion is an order of magnitude smaller than the radial distortion. It rarely goes over 5 pixels in the edge of the image and over 2 pixels in the middle. The decentring distortion is known to vary throughout the time, because the air pressure and shaking of the body have an effect on it.

(Cooper and Robinson, 1996: 21-22; Fryer, 1996.)

3.3.2 Relative Orientation

Relative orientation is needed only when two images are used or stereo pair is presented. In the case of more images, block adjustment is typically employed. During the relative orientation, two images are oriented to the same model coordinate system. The resulting model is uniform compared to the object, but it has an arbitrary scale, rotations and translations. In the orientation, the relative arrangement of the image pair is defined to the same as during the image acquisition – the original epipolar geometry is reconstructed. In the end of the orientation, the image rays of the corresponding points should be intersecting (Fig. 13). Analytically, the relative orientation is performed by measuring the corresponding points and calculating the orientation parameters.

If the interior orientation of the images is known, five unknown parameters need to be solved during the orientation. However, 12 unknown parameters exist: rotations and positions of perspective center for both images. Any five of them can be used, if the chosen parameters are independent. Rest seven parameters will be kept fixed. The problem can also be solved by least square analysis (Mikhail, 1976: 101-109), when the variances of the fixed parameters are determined to be small. (Mikhail *et al.*, 2001: 115-117.)
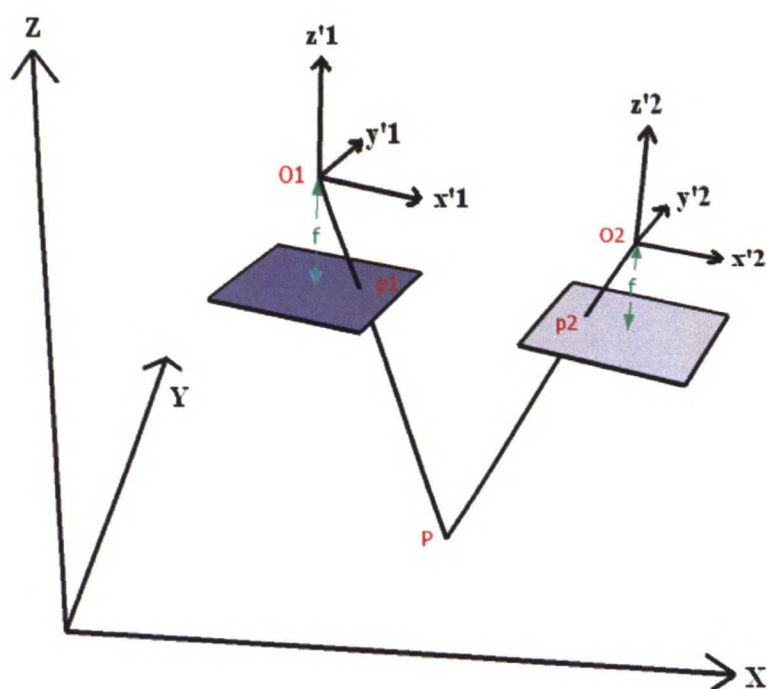
Figure 13. After the relative orientation, the image points p1 and p2 are intersecting in the object point P.

The problems are linear only in the special cases, so the methods are iterative and initial approximates of the unknowns are needed. The methods vary mainly on the selection of the parameters and intersection rules of the corresponding imaging rays. (Mikhail *et al.*, 2001; Schenk, 1999.)

The five parameters can be chosen in several ways, but two main cases exist: *dependent* and *independent* relative orientation. During the dependent orientation, one image is transformed while another has fixed position: the parameters are the two translations and three rotations of the moving photograph. Then, the model coordinate system is defined to be the coordinate system of the fixed image. In the independent relative orientation, both of the images are rotated. The parameters are the κ and ϕ rotations of the both images and ω rotation of an either image. In this case, the x-axis of the model coordinate system is determined to be parallel to the imaging base. In fact, this division of the methods has the roots in the use of analogy stereo instruments and nowadays, the selection of the parameters is almost unlimited. (Mikhail *et al.*, 2001: 116.)

Intersection condition of the corresponding image rays is traditionally implemented based on the collinearity equations or coplanarity rule. Both of the methods are non-linear. In this thesis, method based on the collinearity equations is presented, since as a more universal method, it is more suitable for the convergent photography and the orientation of the several images. It is also a special case of bundle block adjustment, which is employed in the case study and explained in the Chapter 3.3.3.

3.3.2.1 Relative Orientation Based on the Collinearity Equations

According to the collinearity rule, the perspective center, object point and the corresponding image point lies on the same line (Fig. 14).
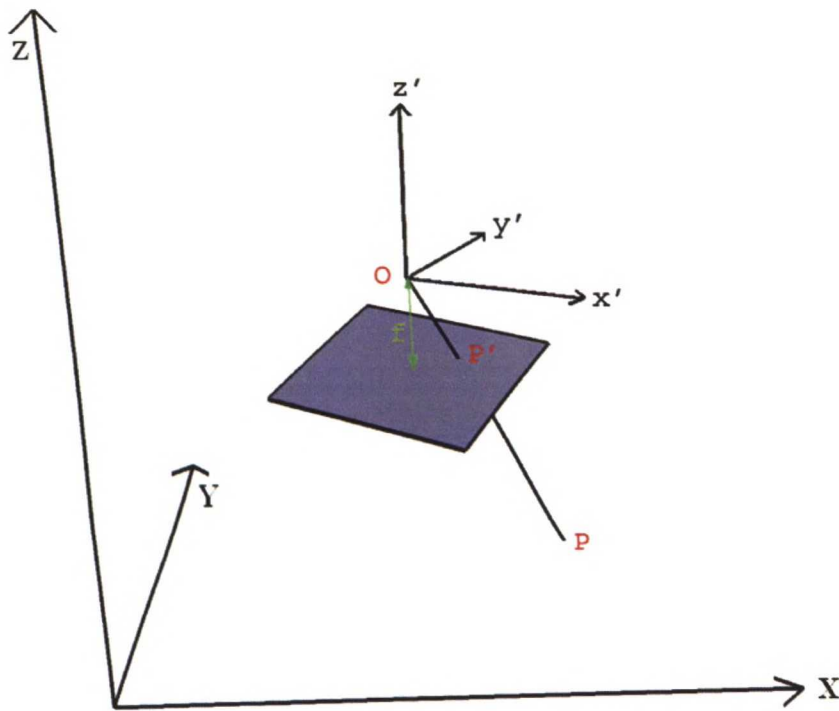
Figure 14. The imaging geometry for one point on a frame image. The collinearity equation states that the perspective center (O), the object point (P) and the corresponding image point (P') lies on the same line. In other words, the collinearity equations defines the relation between the image and the object.

The rule can be written in collinearity equations:

$$x = -f \frac{(X - X_0)r_{11} + (Y - Y_0)r_{12} + (Z - Z_0)r_{13}}{(X - X_0)r_{31} + (Y - Y_0)r_{32} + (Z - Z_0)r_{33}}$$

(6)

$$y = -f \frac{(X - X_0)r_{21} + (Y - Y_0)r_{22} + (Z - Z_0)r_{23}}{(X - X_0)r_{31} + (Y - Y_0)r_{32} + (Z - Z_0)r_{33}}$$

$$R_{\omega\varphi\kappa} = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}$$

$$= \begin{bmatrix} \cos\varphi\cos\kappa & -\cos\varphi\sin\kappa & \cos\varphi \\ \cos\omega\sin\kappa + \sin\omega\sin\cos\kappa & \cos\omega\cos\kappa - \sin\omega\sin\varphi\sin\kappa & -\sin\omega\cos\varphi \\ \sin\omega\sin\kappa - \cos\omega\sin\cos\kappa & \sin\omega\cos\kappa + \cos\omega\sin\varphi\sin\kappa & \cos\omega\cos\varphi \end{bmatrix}$$

(7)

In formulas x and y:

(x, y)   = The image coordinates of the point. The coordinate system has an origin in the principal point and is parallel with the camera coordinate system.

(X, Y, Z)   = The object coordinates of the point

(X_0, Y_0, Z_0) = The position of the perceptive center in the object coordinate system

f   = Principal distance

$r_{11},....,r_{33}$ = The elements of the rotation matrix $R_{\omega\varphi\kappa}$ defining the relation between image and object coordinate systems

ω   = The rotation around the x-axis

φ   = The rotation around the y-axis

κ   = The rotation around the z-axis

(Schenk, 1999: 358.)

30

The five parameters can be chosen either based on dependent or independent relative orientation as discussed in the previous chapter. One image point comprises two equations. In the case of image pair, four equations per point will be established. Since every point adds three unknowns (X, Y, Z) to the problem, redundancy equals to one. Therefore, five points are needed to solve the problem, but with additional points, more accurate result is achieved. Then, every observation constitutes one observation equation and the calculation is done by least square adjustment. Since the method is non-linear, the equations need to be linearized and initial approximations for the unknowns are needed. (Mikhail *et al.,* 2001: 118.)

3.3.3 Bundle Block Adjustment

During the block adjustment, positions and orientations for the bundle of images are calculated simultaneously. In other words, in addition to the relative orientation, also the object coordinates for each image measurement are obtained. As the measured point data is nowadays image coordinates – not model coordinates – bundle block adjustment method is the most used and is therefore reviewed in this thesis. It is also the most accurate and flexible adjustment method employed. Accuracies of 1:500 000 in object coordinates have achieved. Secondly, flexibility comes from the possibility to extend the adjustment with the additional geometrical and navigational data, e.g. known outer orientation elements, GPS measurements or possibility to self-calibration. Conversely, the computational disadvantages of the bundle block adjustment lie into its non-linearity, large data sets and calculation of inverses of large matrices.

The initial observations consist of the point measurements in the image coordinates and control points in the object coordinates. The unknowns to be solved are the six parameters of the exterior orientation of each image and the coordinates of each point in the object coordinates.

The functional model of the bundle block adjustment is the collinearity equations (formulas 6 and 7). The pair of equations is written to every point for every image in which the point can be seen. The solution is usually obtained by the least square method, so the collinearity equations need to be linearized. Unified least squares are

the most commonly applied least square method in this case, as it enables adding of standard deviations for the object coordinates of each point (Mikhail *et al.*, 2001: 412-414).

In practice, differences between the algorithms adjusted to the bundle block adjustment appears in the determination of the initial approximations of the unknowns, and therefore, in the efficiency of the solution. Detailed description of the extended and efficient solutions can be found e.g. by Kraus (1997) and Mikhail *et al.* (2001).

The result of the adjustment needs to be evaluated to reach the specifications of the project. First of all, visual inspection can be employed to reveal trends of obviously incorrect inputs. The statistical analysis is also used to detect the quality of observations, but particularly the quality of the adjustment in general. The accuracy of the adjustment depends on the imaging geometry (the number and quality of the intersection rays), control point arrangement and accuracies, and the shape of the target. Typically, software calculates at least the RMS residuals of each point.

(Mikhael *et al.,* 2001: 119-123; Kraus, 1993.)

Chapter 4

The Case Study: Finnish Jabal Haroun Project
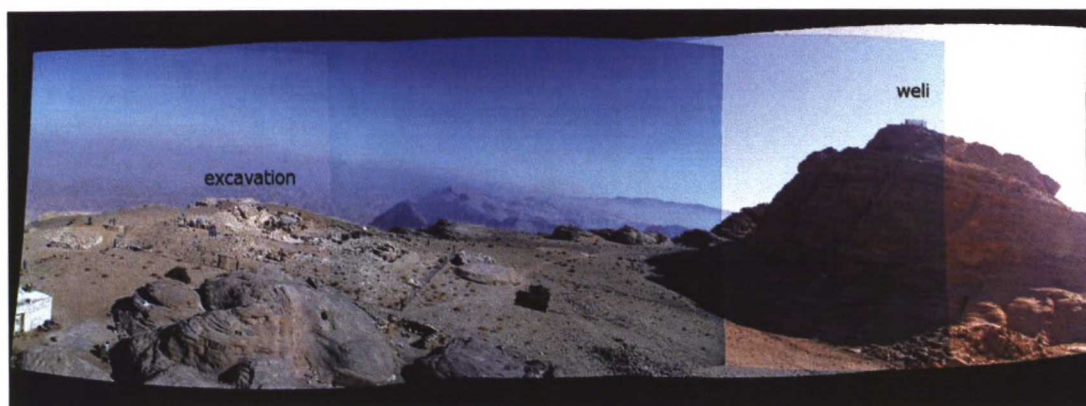
Figure 15. The excavation area of FJHP on the Jabal Haroun plateau at 1250 meters above the sea level. The burial place of Aaron (weli) lies on the summit of Jabal Haroun on the right hand side. (FJHP/Petteri Pöntinen)

In this chapter, photogrammetric documentation methods and related activities in the archaeological excavation process are described through the case study in Finnish Jabal Haroun Project (FJHP). The photogrammetric data, processes, products, archive, uses of the products and future needs are also compiled into the flow chart (Fig. 16).

Finnish archaeological investigations have rather long traditions in the Near East, but the FJHP is the first large-scale project. The FJHP excavations has taken place on Jabal Haroun – "the Mountain of the Prophet Aaron" – which locates about 5

kilometres southwest from Petra, in Jordan. According to the Jewish, Christian and Muslim tradition, the mountain is the burial place of Moses' brother Aaron and it has been a pilgrimage site at least since the Byzantine time. On the Jabal Haroun plateau, about 70 meters below the summit, there is an extensive,
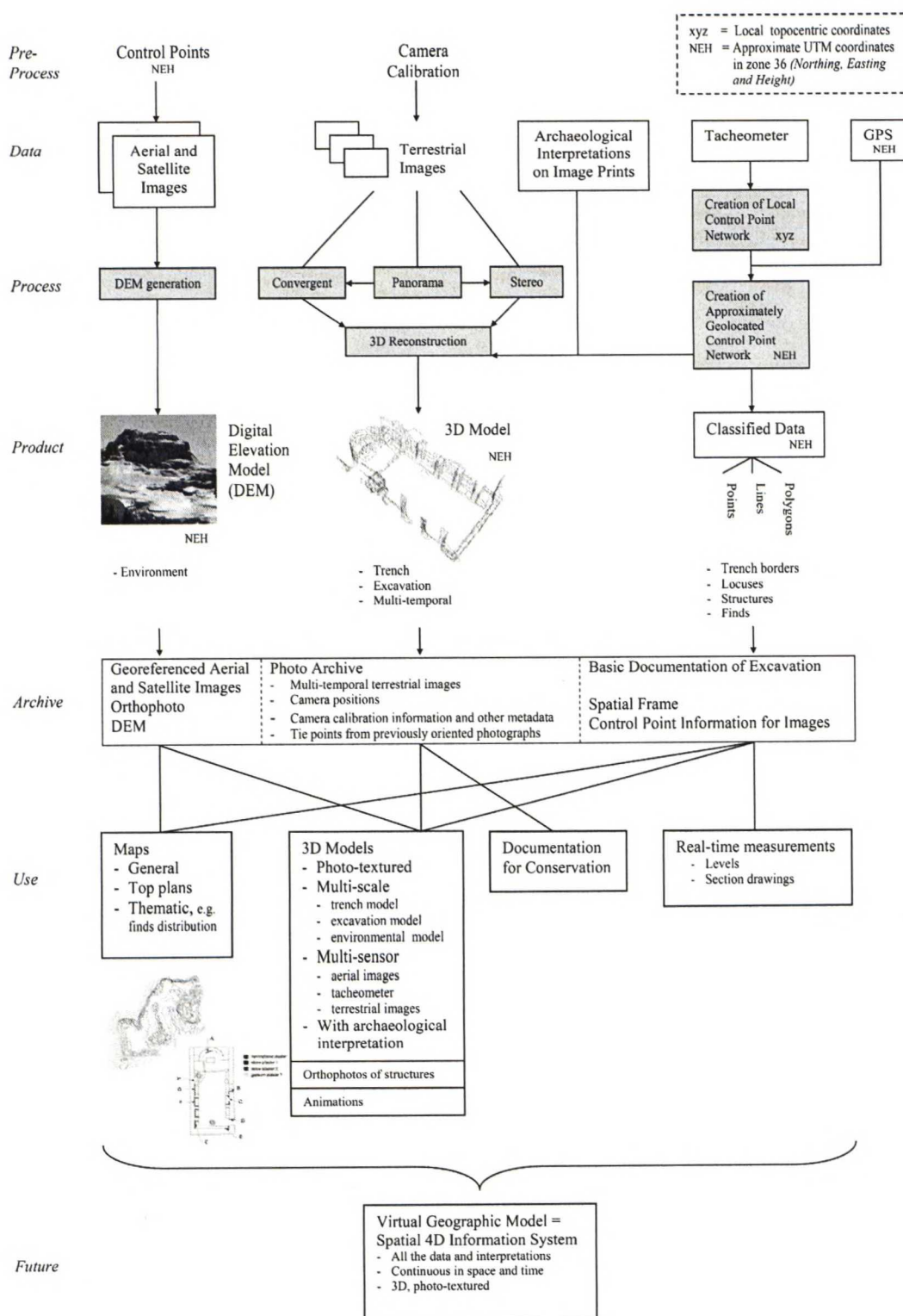
Figure 16. Photogrammetric and geodetic activities in the FJHP excavations.

ruined architectural complex (Fig. 15). This is thought to have been a Byzantine monastery (app. 400-700 AD) and has been the center of the Finnish investigations. However, the re-used stones in the site indicate construction activities as early as in the Nabataean-era (app. 300 BC - 100 AD). Due to the vicinity to both Wadi Arabah and the Petra Valley, a watchtower or a sanctuary are the possible interpretations of these constructions. Human activities on the site are also found from the Islamic periods, and signs of the monastic life last until Crusades (app. 1200 AD). (Frösén *et al.*, 1998; Fiema *et al.*, 2007.)

Besides the monastic complex, the interest of the archaeologists has extended to the surrounding environment. The survey team of the project has conducted an intensive survey of the 6 km^2 area in 1998-2005 (Fig. 17) and an additional extensive survey of 7 km^2 in 2005. The preliminary results of the archaeological survey in FJHP can be found in Lavento *et al.* (2006).
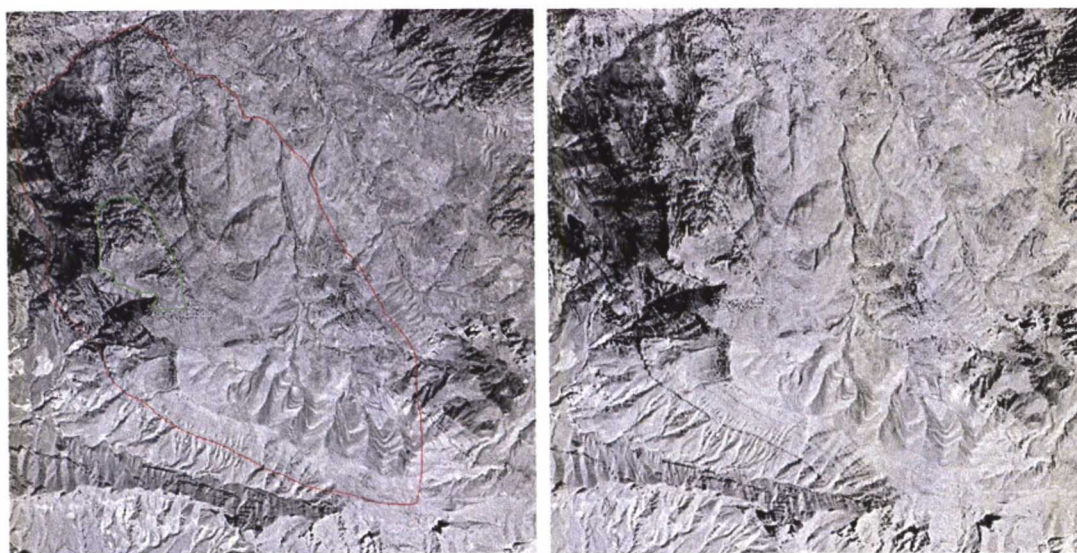
Figure 17. Corona KH-4A satellite stereo image from Jabal Haroun. The plateau of Jabal Haroun is indicated by green outline and the intensive survey area by red line. The stereo image pair was acquired in 1968 with the approximate spatial resolution of 4 meters. The north is pointing to the left, into same direction as the imaging base, and each image corresponds to 2.5 x 2.5 kilometers. The stereo impression can be obtained by crossed viewing direction.

Data available from U.S. Geological Survey, EROS Data Center, Sioux Falls, SD.

The research unit of "Ancient Greek Written Sources" is responsible for the project under the leadership of professor Jaakko Frösén. It is working at the University of Helsinki in the Department of Classical Philology. The unit is a Centre of Excellence of the Academy of Finland in 2000-2011. The Institute of Photogrammetry and Remote Sensing (TKK) has participated the project from the beginning in 1997.

4.1 Technical Settings

4.1.1 Hardware

For the terrestrial photogrammetry, the project has used both video and frame cameras. These cameras are presented in table 1 and part of the equipment is shown in figure 18. For the purpose of panorama photography, mechanical cross-slide mounts were used (Fig. 19).

Table 1. Cameras used for photogrammetric documentation in FJHP. (FJHP/Nina Heiska and Hanne Junnilainen)

Camera	Time period	MPixels/pixels	Memory capacity (MB)
Olympus Camedia-1400 (Frame camera)	1997-2003	1.4/1280 x 1024	4, 8, 16, 32, 256
Sony Handycam CCD-TR780E (Video camera)	1997-1999	App. 640x480	
Olympus Camedia-4000 (Frame camera)	2003, 2005	4.0/2288 x 1712	256

Figure 18. Part of camera equipment in FJHP. (FJHP/Nina Heiska and Hanne Junnilainen)

Figure 19. The cross-slide used for panorama photography.

In order to eliminate distortions caused by camera, each camera has been calibrated regularly and prior to the field seasons. During the years, two test-field calibration techniques have been used: the *calib* software and the *iWitness* software (iWitness, 2007). The calib software was developed at the TKK for a test-field, which has stable and measured targets, whereas the *iWitness* software works with the targets that are distributed arbitrarily (Fig. 20). The significance of the camera calibration can be seen in the final result, e.g. on the edge of the image, the distortion caused by the Camedia-4000 is 54 pixels. An average RMS-value of 0.09 pixels was achieved in the *iWitness* calibrations. In the *PhotoModeler Pro* (PhotoModeler Pro, 2004), the camera may also be calibrated as a part of the modeling process – with no prior

knowledge – as a self-calibration. However, in the case of FJHP where the objects are geometrically unformed and the use of targets is unfeasible, the image acquisition would become too complicated if self-calibration had been used.

In the fieldwork, images should be captured with the same parameters as during the calibration, including the same zoom, focus and aperture. The most influencing parameter, the zoom, is easily kept unchanged, however it is difficult to keep the focus constant if images are taken from different distances, e.g. when attaching details to general photogrammetric models.

Figure 20. Camera self-calibration with the iWitness test-field.

GPS measurements for the creation of control point network were done with the three pieces of Ashtech LM XII receivers in 1998. Since then, the electronic measurement equipment for the basic documentation has consisted *Geodimeter 600* series tacheometer and its basic equipment. To ensure the required quality of the measurements, tacheometers were calibrated at the TKK. The results showed that

the index disc uncertainty was below 0.5 mgon and the mean and constant errors of the distance were below 1 millimetre.

After the data acquisition, the images and the tacheometer data were downloaded into two laptops, which were available for editing and storing of the data. The equipment included also a black-and-white printer and later a color printer, which were used to produce image prints for sketches.

In the beginning, the data was saved in 100 MB Iomega zips. Nowadays, laptops have CD-ROM or DVD burning capability available even in the harsh conditions of Jabal Haroun. Technical support services were not easily available and therefore, each mechanical device or software had to have a back up.

Additionally, the local environment set requirements for the devices. First of all, the ubiquitous fine sand eventually destroyed all mechanical equipment, unless it was somehow protected. Therefore, the cameras, computers and related equipment were kept as protected as possible inside the tents. Another environmental constraint was the electricity, which was not available in abundant amounts. It was produced by two sets of Neste NAPS solar panels and stored in car batteries.

(Junnilainen *et al.,* 2007.)

4.1.2 Software

During the years, several computer programs has been tested and used to process and store the data. The software is listed in table 2. In the case of photogrammetric software, several programs were tested and five were developed by the TKK. In the end, only a few of them were actually used in the final modeling procedure: *iWitness* and *PhotoModeler* for 3D modeling; *Comb* and *Poc* for panorama images; and *ImageStation*, *MicroStation* and *TerraModeler* for DEMs. However, the lack of software capable for automating photogrammetric processes is still tangible and the programs need to be developed further even though they have improved considerably throughout the years. In the beginning, for instance, the *Calib* and the

Coma software were needed for camera calibration, but these days calibration is commonly part of every photogrammetric software.

Tacheometer data processing procedure was successfully developed and standardized using *Geotool* and *MicroStation*. In particular, the *TerraSurvey* module, which is used as part of MicroStation, proved to be advantageous.

Software	Use	Manufacturer
Mission Planning	Schedule planning of the GPS measurements	Ashtech Corporation
Winprism 1.0	Vector calculation of the GPS measurements	Ashtech Corporation
Xglobal System	Network adjustment of the GPS measurements	X-position Oy
ImageStation	DEM	Integraph
Geotool	Tacheometer data transfer and conversion	Trimble
MicroStation SE and V8	GIS, modeling and visualization	Bentley Systems
TerraSurvey	Reading and classification of spatial data	Terrasolid Ltd.
TerraModeler	Modeling and visualization of spatial data	Terrasolid Ltd.
ArchiCAD	Top plan of the excavation	Graphisoft
AutoCAD	Cartography and visualization	Autodesk
MapInfo	Cartography	MapInfo
Calib	Camera calibration	TKK
Coma	Compensation of camera distortions	TKK
iWitness 1.2.3.	Camera calibration	Photometrix
Comb and Poc	Panorama images	TKK
Rectcc	Projective transformation and combination of images	TKK
Geomatica	Image rectification, DEM, Orthophoto	PCI Geomatics
PhotoModeler Pro 5	3D modelling	Eos Systems Inc.
PhotoShop	Image processing	Adobe
IrfanView	Image processing	Irfan Skiljan
MS Office Tools	Data processing, documentation and archival	Microsoft

Table 2. The software used during the project. (FJHP/Nina Heiska and Hanne Junnilainen) (Junnilainen *et al.,* 2007.)

4.1.3 Data

The data and their uses in the FJHP is presented in table 3.

Table 3. The data acquired in the FJHP excavations.

Data	Amount	Acquisition Year	Use
Aerial images 1:15 000 *Stereo coverage* *Grayscale* *No control points*	15	1981	Map and DEM Production
Aerial images 1:30 000 *Stereo coverage* *Grayscale* *No control points*	8	1992	Map and DEM Production
Topographical Map 1:50 000	1	Unknown	Geo-referencing of the aerial images
KVR-1000 Orthophoto *Grayscale* *Resolution 1,5 m*	1	2001	Geo-referencing of the aerial images
KVR DEM	1	2001	Geo-referencing of the aerial images
Terrestrial Images	App. 12 000	1997-2005	Photogrammetric documentation
Tacheometer Data	Every deposit and feature excavated. Part of the findings.	1998-2005	Creation of the control point network Documentation of the excavation process Auxiliary information for image orientation Real-time measurements for the archaeologist
Static relative GPS measurements	8 points	1998	Creation of the control point network Geolocation of the local coordinates
Archaeological interpretations on image prints	Every locus of trench A1, 9 phases	2005	To measure and visualize archaeological features by photogrammetry

4.2 The Establishment of the Spatial Frame

At the outset, the need for the cartographic work arose from the lack of detailed maps. Furthermore, due the limitations on aerial photography in Jordan, the project was not able to produce its own aerial photography for mapping purposes. Therefore, before any excavation took place, a digital elevation model (DEM) and the map of the Jabal Haroun was produced from the available 1:15'000 aerial stereo photography by SITO (SITO, 2007). The DEM was custom-made and geodetically referenced using the 1:50'000 topographic map (Figs. 21 a-b). As there were no targeted control points in the photography, the geo-referencing was relatively

inaccurate, and thus the quality of the map was inadequate. The DEM was later expanded to cover the surveying area of the project. In 2001, new image material, a KVR orthophoto with 2 meters ground resolution and respective DEM, was obtained. In 2005-2006, the accuracy of the original DEM was further improved by using the KVR orthophoto as geo-reference. Also a general map of the Petra area was made based on the KVR orthophoto (Fig. 22). (Junnilainen *et al.*, 2007.)
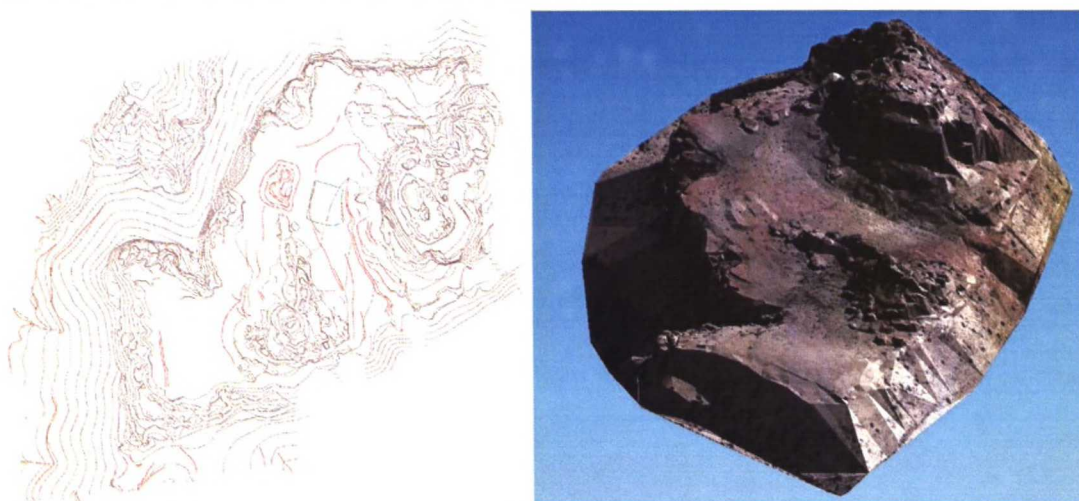
Figures 21 a-b. Digital elevation model (DEM) of Jabal Haroun represented by contour and break lines (a) and textured with an aerial image (b). (FJHP/Hanne Junnilainen and Riku Karjalainen)

In addition to the general map of the area, a trigonometric control point network for more detailed measurements was established around the excavation area at the Jabal Haroun plateau. It comprises five metal rods, which were drilled into the bedrock and spread evenly and visibly around the site (Fig. 23). The trigonometric network was measured by tacheometer using the mean values of both angle and distance measurements. The resulting data was further processed and adjusted using the least-square analysis, and the final accuracy of one centimetre in local topocentric coordinates was achieved. The network was later expanded by using static relative GPS positioning (Wells *et al.,* 1986: ch. 4.19-4.20) in vector calculation and tacheometer in the definition of the local geoid (Wells *et al.*, 1986: ch. 11.3). Since accurate control point information was not attainable, the network was built as a true free network. At the same time, the local coordinate system was approximately tied into the Jordanian national coordinate system (UTM, zone 36) by a datum transformation and with one known elevation point. This was a prerequisite by Jordanian Antiquites, as the data integration into the Jordanian archaeological
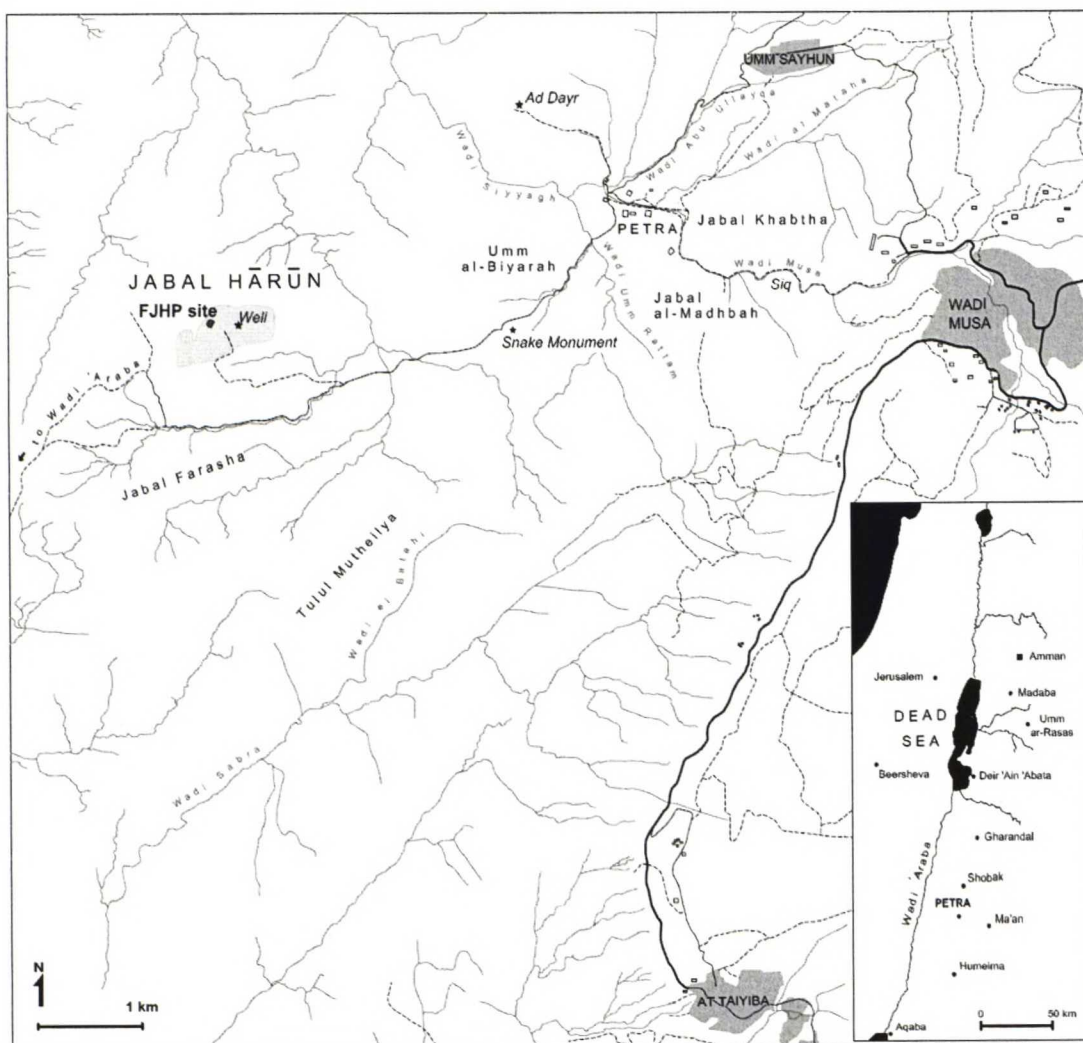
Figure 22. General map of the Petra area and Jabal Haroun. It is produced based on the KVR orthophoto.

geographic information system should be feasible. As a result, a good accuracy in local coordinates was achieved, but the global coordinates remain approximate. The task of the expanded network was done by Petri Honkanen and Matti Rantanen from Espoo and Vantaa University of Applied Science (EVTEK). Further information of the network creation and relating accuracies can be found from Honkanen's Bachelor's thesis (Honkanen, 1999).

The control points were documented by photographing and mapping their location. In the beginning of each excavation season, the stability of the points was checked to ensure the good quality of the measurements. During the seasons, only one point, which was situated in the middle of the site, became useless as it was removed during the excavation. (Junnilainen *et al.*, 2007.)

43
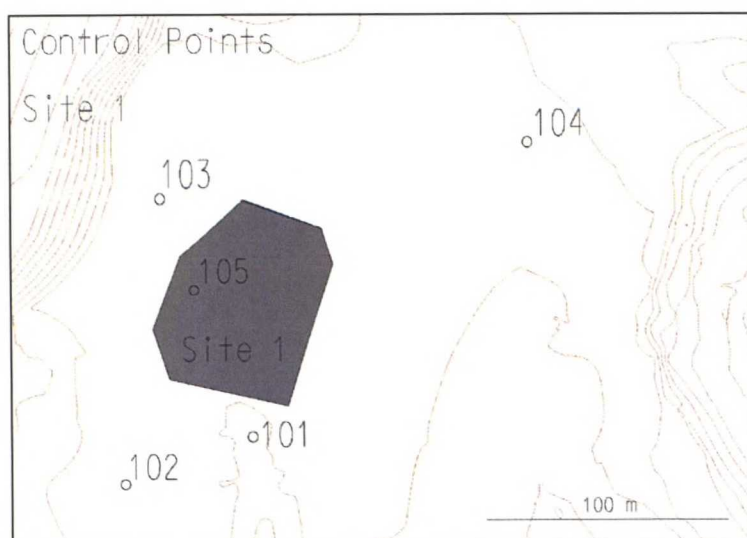
Figure 23 Control point network in relation to the excavation area.

4.3 Tacheometer Measurements in the Documentation

Tacheometers have been used on documentation of the excavation process for quite some time now (e.g. Powlesland *et al.*, 1998; Vote 2001: 109; Cosmas *et al.*, 2001: 300; Doneus and Neubauer, 2005) and the surveying principles can be found out on a number of land surveying or archaeological manuals (e.g. Kahmen and Faig, 1988: 131-132; Bannister *et al.*, 1998: 134-163; Burke and Smith, 2004: 104-114). (Junnilainen *et al.* 2007.)

In FJHP, tacheometer measurements have been done for four purposes: to create the trigonometric control point network; to do the basic documentation of the excavation process besides the photogrammetric documentation; to obtain georeference for the images; and to acquire real-time measurements for the archaeologist on the site. Since this thesis concentrates on the photogrammetric documentation, the tacheometer documentation process is not reviewed, but the detailed description can be found by Junnilainen *et al.* (2007). However, from the photogrammetric point of view, tacheometer measurements have important role in the geoferencing of the images and 3D models. So far, pointwise geo-referencing has been done, but feature based orientation methods can be used as well as the basic tacheometer data is classified (Figs. 24 a-b). On the other hand, tacheometer and photogrammetric techniques are supplementary in their nature (Table 4). E.g. positioning of the significant findings and real-time measurements for the

archaeologists could not have conveniently been done by photogrammetric means. Still, these had an important role in the archaeological work – e.g. real-time measurements were used for level measurements and auxiliary information for the dimensional drawings.
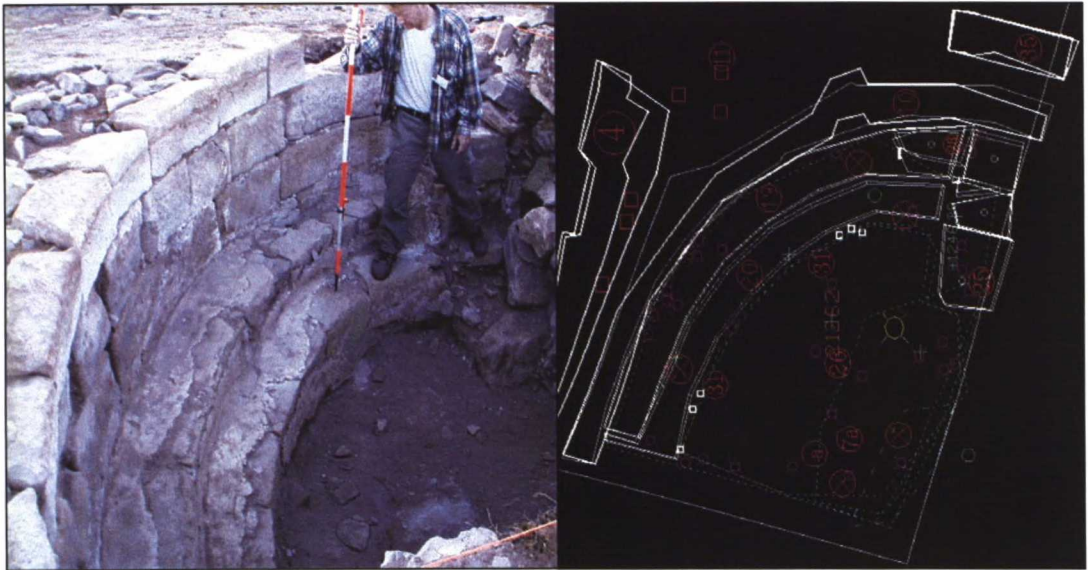
Figures 24 a-b. Tacheometer measurements of the apse of the church and the corresponding photograph. The data is classified according to the coding system created in 1998. Following archaeological features has consistently been measured during the excavation process: the tops and bottoms of the deposits; the 3D shapes of the structures; and the position of selected findings.

Table 4. Comparison of tacheometer and photogrammetric documentation in excavation.

Tacheometer Documentation	Photogrammetric Documentation
Acquisition is done during the excavation work and is more time consuming	Faster acquisition Does not disturb the excavation work
	Site need to be emptied before acquisition
	Lighting conditions need to be even
The site need to be touched	The site remains untouched
Accuracy cm (in local coordinate system)	Accuracy 1:1000
Measurements are done in used coordinate system	Tacheometer measurements are needed to geo-reference the photogrammetric measurements
Less post-processing	Time consuming post-processing
Measurements for real-time use on site, e.g. levels	
Data classification is done during the acquisition	Only some of the interpretations are done on site Produces base for the classification Interpretation results are comparable on images
Only the interpreted data is left	Photo archive Interpretations with new research questions can be done
No texture	Photo-texture increases realism and data content
3D modelling is rough	3D modelling is more detailed and can be done more specifically later on

4.4 Photogrammetric Documentation and 3D Modeling

The photogrammetric objectives of the FJHP have been twofold. The original aim was to reconstruct a virtual geographic model for the entire archaeological project and to document the excavations. The virtual geographic model is considered to be a 3D frame in which all the photogrammetric, geodetic and archaeological data and interpretations would be projected and stored. The second objective has been to develop useful concepts for archaeological documentation using photogrammetry and to acquire data in a way that it can be used to answer different questions and research goals in the future. Thus, the photographs serve as a visual diary and they can later be used for example in recovering data. In this respect, the value of the photographs lies in their non-interpreted characteristic. (Junnilainen *et al.*, 2007.)

In FJHP, several photogrammetric methods have been applied during the years. Recording for the multi-temporal archaeological documentation was carried out in such way that the images can now and in the future be used for photogrammetric 3D reconstruction. These techniques aim to be convenient in difficult field conditions, user-friendly and manageable by non-photogrammetric experts such as archaeologists. The digital images have also been utilized to record specific information related to the conservation work. During the early years of the project, experiments were conducted to find out the best work routines in the field. Three aspects rose above other considerations: when to take the photographs; how to keep record of the photographs; and how to signalize the control points on the photogrammetric images. (Junnilainen *et al.*, 2007.)

As an important task of the photogrammetric documentation, 3D modelling process of the object has been emphasized. At the moment, the 3D modeling procedure has been developed and tested and is presented in the following chapters. In the beginning, the procedure was successfully tested with images which were not specifically acquired for this 3D modeling technique, but later on, image acquisition has been standardized for the purpose. At any rate, images for modeling of each stage of the excavation have been acquired and the modeling can be completed later.

In the FJHP, the aim of the 3D modeling has been to develop procedures to build factual, photo-textured 3D models of archaeological excavations and their surroundings. The common and consistent coordinate frame for all the models has been the prerequisite of the research problem. From the archaeological point of view, the aims of the 3D modeling are to document the archaeological excavation, to visualize and to document the process of the excavation, and to support archaeologists in their analyses. The following requirements for 3D models have been specified during the project: high geometrical accuracy; photo-texture; visual realism; capture of details; portability of measuring equipment; and low cost. Also model size efficiency; application flexibility; and sufficient level of automation are defined to be advantageous features. However, a system that satisfies all the requests is still in the future (Remondino and El-Hakim, 2006: 272).

A 3D model has two components: the geometrical model defines the shape of the scene and the radiometrical model determines the appearance – the texture of the surface. Basically, the shape is approximated by adjoining surface polygons and the texture-elements are projected onto the corresponding polygons. In photo-textured models, the texture is taken from equivalent photographs. (Figs. 25 a-b)
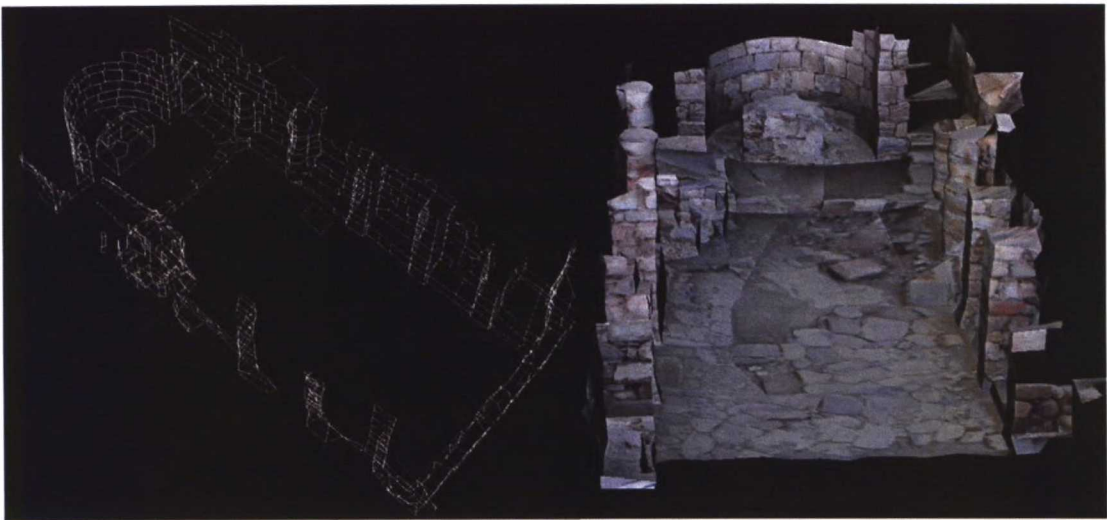
Figures 25 a-b. 3D models of the chapel. The shape of the scene is presented in a wire-frame model (a) and the real-like appearance is combined to the geometrical model by photo-texturing the surface polygons (b). Photo-textured models are realistic and abundant in details. (FJHP/Anna Erving)

The modeling requires geometric data acquired by sensors ranging from digital and video cameras to laser scanners. We present an image-based approach based on a

digital camera and tacheometer. The source material, multi-temporal image series and geo-referencing data, has been collected during 1998-2005. The *PhotoModeler Pro 5*, a photogrammetric modeling software, was chosen since it has potential to create geometrically correct photo-textured models in a straightforward manner. The process of the modeling is presented in figure 26 and will be explained in following sections.

In practice, entities such as a single trench, phase of the excavation process, or aisle of the church have been modeled at a time. These correspond to the area of app. 4 x 7 meters and 50–100 modeling images. It must be noted that the software runs considerably slower if more images and larger areas are modeled at once. On the other hand, it is easier for a person to comprehend a distinctive scene and manage limited amount of images. Afterwards the separate models can be oriented together.

At the moment, large part of the church, chapel, mosaic floor and trench A1 has been modelled. In trench A1, also the progress of the excavation – stratigraphic layers – has been documented by 3D models.
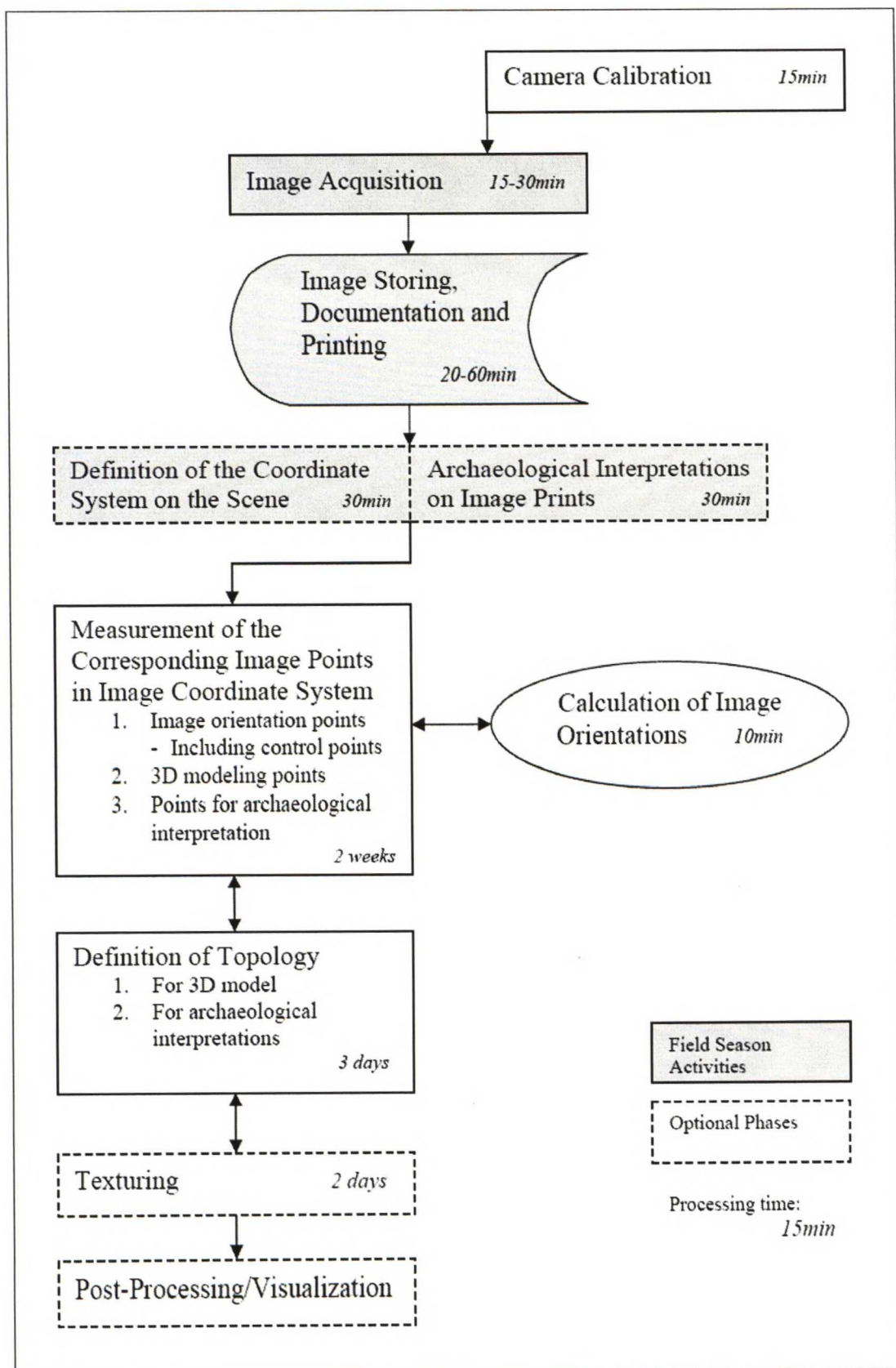
Figure 26. Photogrammetric 3D modeling process of an archaeological excavation entity.
Process and processing times are suggestive; some of the phases are performed simultaneously
or iteratively and are optional, depending on modeling objectives.

4.4.1 Image Acquisition

The image acquisition is an important and demanding task in the photogrammetric modeling process. The case of archaeological excavation is particularly challenging, as the photography can rarely be repeated, sites are complex, and 3D modelling is need to be done in multi-scale and multi-temporal. Additionally, the time for imaging is limited, since the excavation process is fast-paced and the lightning conditions are changing rapidly.

First of all, it was necessary to define the best time of the day to take photographs. The lighting conditions in the desert are very challenging - strong contrasts - and unfortunately, the digital cameras are very sensitive to it. Technically, homogenous lighting conditions make it easier to combine, measure and visualize the images. The timing of the photography was also related to the progress of the excavation because it was important to disturb the excavation process as little as possible. Consequently, early mornings proved to be ideal for photo sessions as the lighting is usually more constant before the sun rises above the summit of the Jabal Haroun. As a result, each excavation trench has been documented with photogrammetric images every morning and therefore, the changes in the trenches can be traced within 24-hour cycles. When necessary, the photogrammetric images were taken while the excavation work was in process or after the work in the evening, when the lighting conditions were suitable as well. The archaeological team has also photographed the trenches during the day and therefore, some of the changes can be detected within a sub-daily level. (Junnilainen *et al.*, 2007.)

In FJHP, panoramic, stereo and convergent imaging techniques have been employed. Furthermore, the panorama photographs can be applied both for stereo and convergent imaging. Convergent images have the main role in the photogrammetric documentation and 3D modelling as they enable the good imaging geometry and image acquisition of the complex site is practical. In the case of convergent photography, the camera network design has an important role and is discussed in the Chapter 4.4.1.4.

4.4.1.1 Panoramic Photography

The use of panoramic images for photogrammetric documentation has been extensively studied during the FJHP since the first field seasons in 1997 (Haggrén *et al.*, 1998; Pöntinen, 1999). Panoramic photography has proved to be particularly suitable for documenting archaeological views or structures, which are difficult to document with ordinary images, such as exterior and interior surroundings or elongated objects (Figs. 27, 28 a-c, and 29). It has primarily been applied to the collection of convergent image blocks for photogrammetric documentation to be used for 3D modeling of excavations. Also the use of panoramic images in stereo measuring has been studied (Nuikka, 2002). (Junnilainen *et al.*, 2007.)
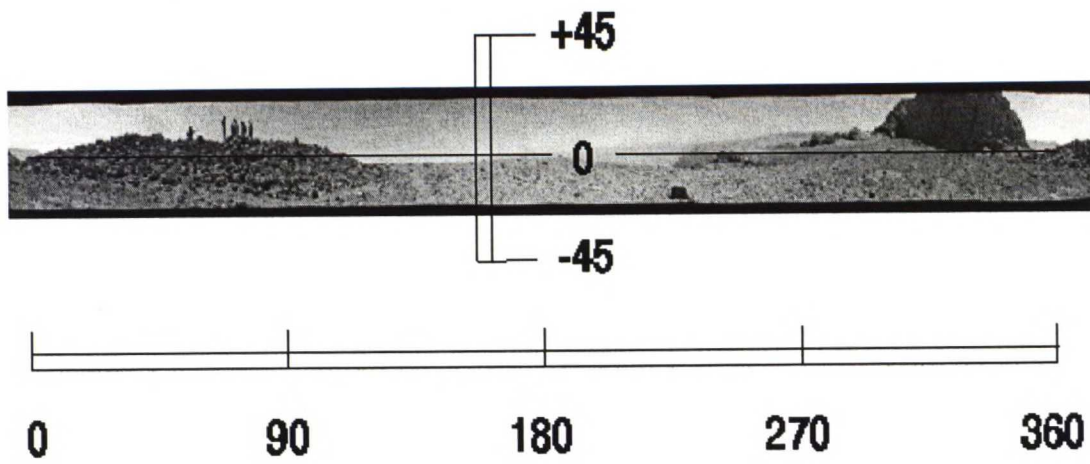
Figure 27. Panoramic image of a wide area. The photography was acquired at the excavation area in 1997. The image is created from a video sequence by rotating the camera the full circle of 360 degrees. (FJHP/Henrik Haggrén and Petteri Pöntinen)
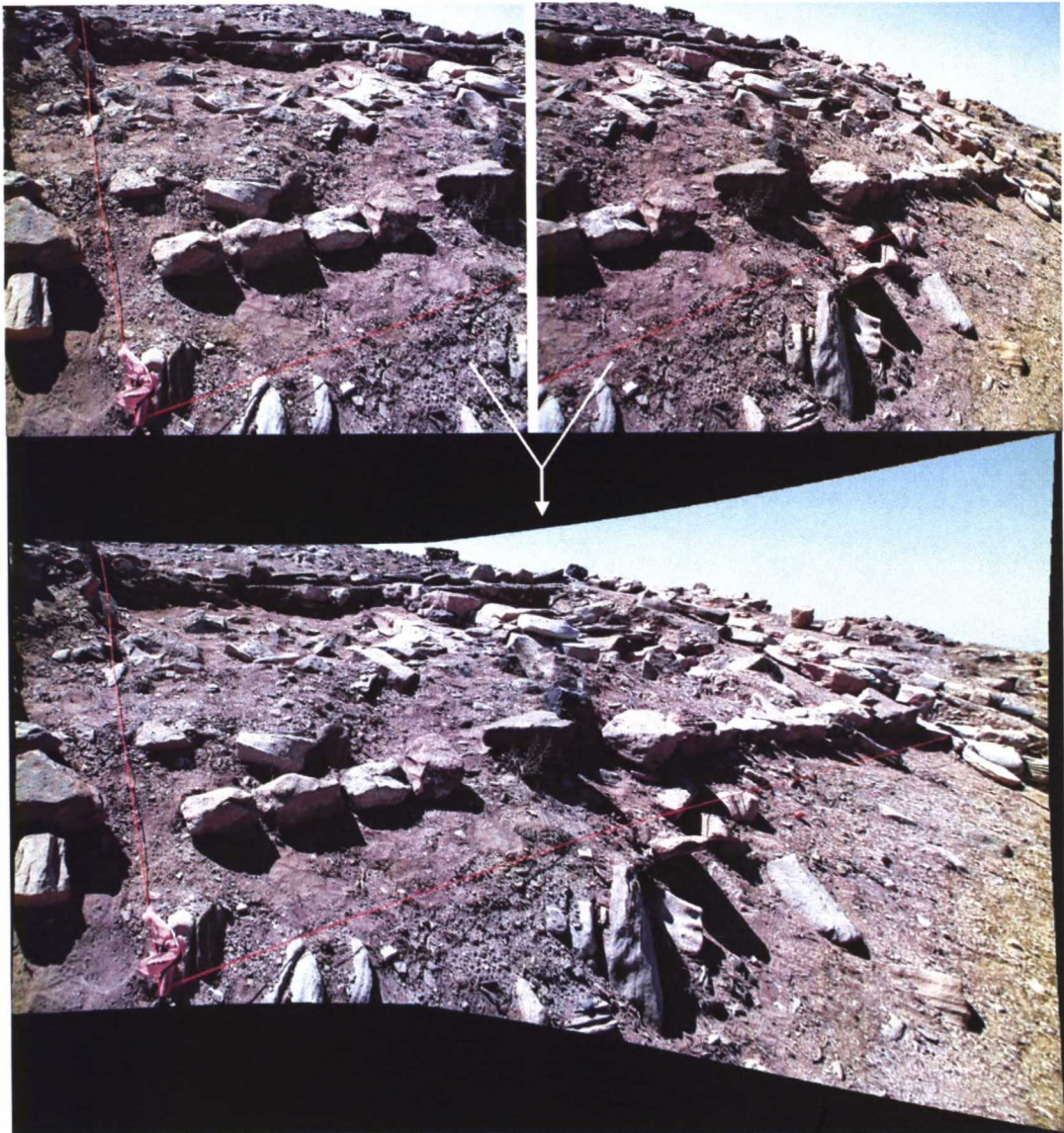
Figures 28 a-c. Two images (a-b) and their panoramic composite (c) as part of the photogrammetric documentation of the excavation. (FJHP/Petteri Pöntinen)

Figure 29. An interior panoramic image of a wall of an apse of the church. The original images are captured with a digital camera and transformed to a cylinder frame. This sequence of five concentric images corresponds to an approximate angle of view of 40° x 210°. (FJHP/Jaakko Järvinen)

4.4.1.2 Stereo Photography

In FJHP, stereo photography has mainly been applied to the visualization and interpretation purposes. As far as the archaeological interpretation is regarded, stereoscopic views reveal spatial relationships within the trench much better than single images. The third dimension in viewing will also subsequently provide additional information for superimposing any complementary graphical data in the scene. From the archaeological point of view, the stereo photographs can also be seen as an objective presentation of the object compared to interpreted manual sketches (Schuhr and Kanngieser, 2006). (Junnilainen *et al.,* 2007.)

In FJHP, stereo images have been taken according to the normal case of stereo photography as presented in Chapter 3.2.2. In the presentation of the stereo images, both techniques of anaglyph (Fig. 30) and separate images (Fig. 31) have been used.

Figure 30. Anaglyph stereo pair of the babtistery. For viewing, one needs anaglyphic glasses with respective red and cyan filters. (FJHP/Henrik Haggrén)

Figure 31. A stereo pair of the babtistery. This 3D view can be seen by crossed viewing. (FJHP/Henrik Haggrén)

4.4.1.3 Camera Network Design

The camera network design problem was initially divided according to the components of a 3D model: the geometrical- and radiometrical model. Firstly, the convergent images for the geometrical model were captured with notion of 'generic network' (Chapter 3.2.4.). Secondly, photography for the radiometrical model – texture – was taken orthogonally to the object, with a high image resolution and without any visible obstacles.

In the case of geometrical imaging, excavation trenches have further been divided into to sub-networks, e.g. a wall, pilaster, partition wall, floor, and millstone. Each sub-network has been then imaged according to the idea of 'generic network', basically in a way that every individual object point appears at least on 2-3 photographs and the angle between the camera positions is between 60-120 degrees (Fig. 32). Thereafter, the general images were attained to tie these sub-networks into one image block with sufficient geometric strength.
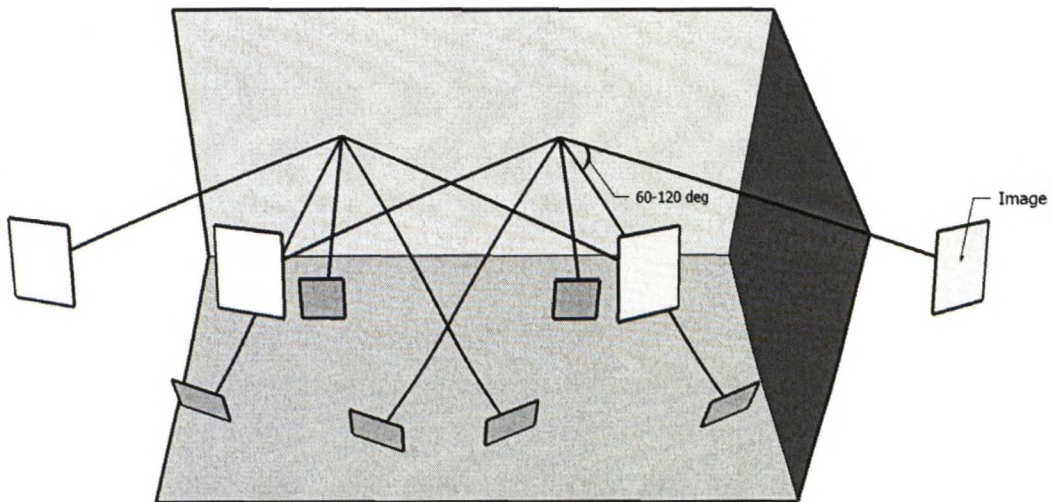
Figure 32. Simplified convergent camera network of one trench wall. Texture images are taken perpendicularly to the wall.

Since archaeological sites are usually geometrically unformed, defined requirements for the 3D models (Chapter 4.4.) are demanding. As a main concern, self-occlusion by the object shape occurs and even with careful planning, shadows remain easily. Consequently, geometrically challenging object lead to the situation where numerous images have been taken from close range. In other words, a complex

object is full of sub 'generic networks' and shadows exist in between the networks. Practice has shown that it is recommended to capture additional images, even when the imaging geometry has been planned carefully. In many modeling cases, imaging quantity has compensated the quality. (Fig. 33 a-b) In particular, the texture imaging of the floors has been laborious because of the non-optimal imaging angles.
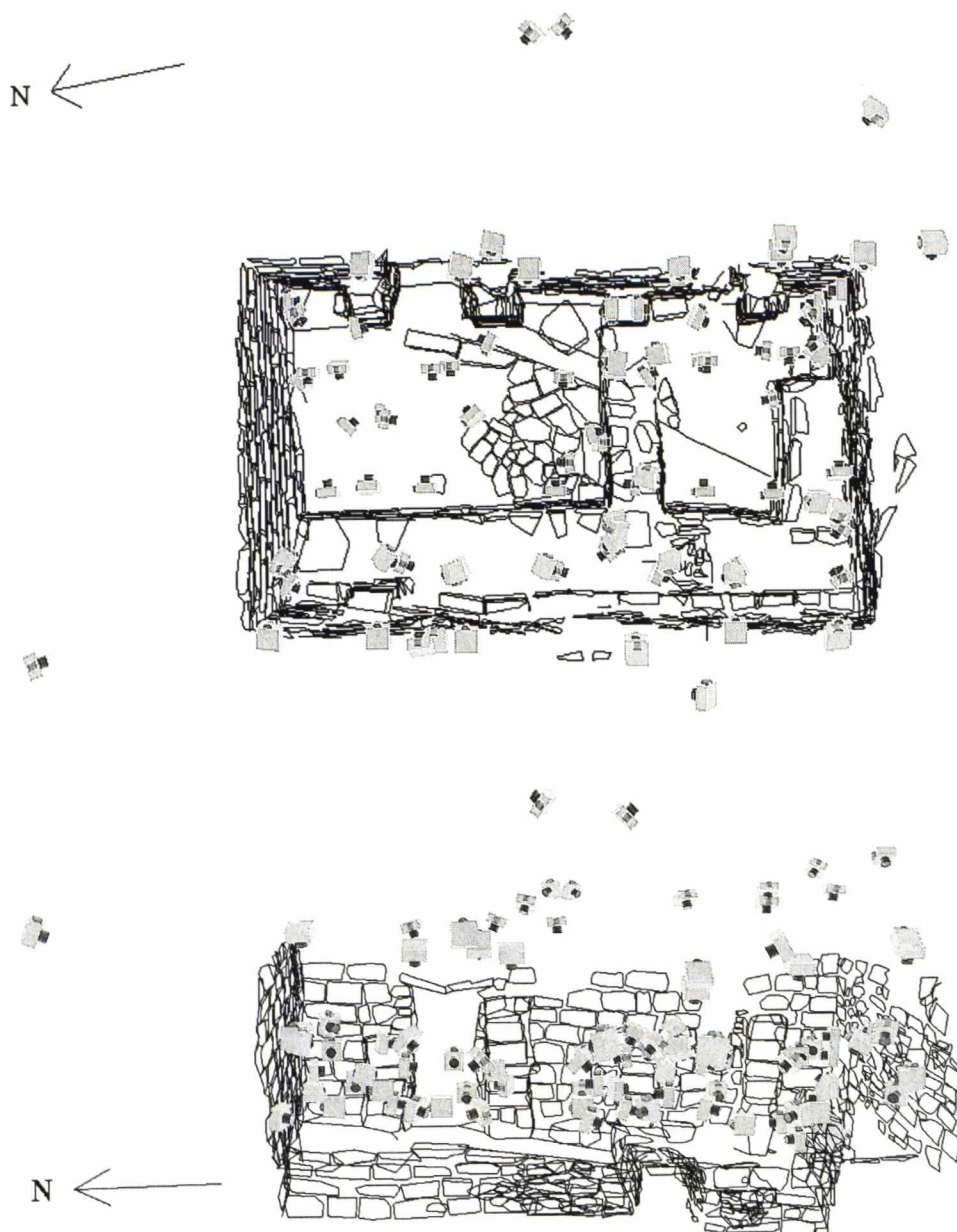
Figures 33 a-b. Camera positions on top view (a) and side view (b) of trench A1. In this case, totally 102 images were used for modeling. The trench was first divided into sub 'generic networks'. Subsequently numerous images were captured in close range, especially of important details, e.g. pilasters and a millstone. Broad view imaging was done to tie detailed photographs to a one image block. Better imaging geometry, which means using wider camera angles, was achieved by taking images from outside of the trench and by using ladders. A tripod improved the image quality and enabled the use of the same aperture as in the camera calibration.

4.4.2 Image Storing and Documentation

During the project, the TKK team has acquired comprehensive collection of photographs taken regularly during the progress of the excavation. To keep track of the images, their thumbnails were copied to HTML files to create a photo diary (Koistinen *et al.* 2001). In this record, the images have been organized by the date and the preliminary geo-referencing, as well as by other relevant information, such as camera and the imaging technique and control point information. Later, the images for one model were stored in a folder, in which separate modelled parts, such as walls, were further saved in sub-folders. In time, it was noticed that the HTML files were not suitable for storing metadata because the data cannot be queried efficiently. However, good geospatial data management is required when the images are processed further. After all, the image storing and documentation is required to be done in a manner that a person without prior knowledge can find the essential data and perform the modeling. (Junnilainen *et al.*, 2007.)

In practice, the time left for documentation during the field season is restricted. Even the collection of the camera positions by hand is almost unattainable which is why automated systems would be advantageous. Ideally, the camera would automatically collect the position (e.g. GeoSpatial Experts, 2006; RoboGEO, 2007) and the angle of bearing of imaging. Subsequently, the positions, the angles, descriptive information of the target and imaging, and images themselves would be transferred to a graphical interface and images could be queried by attributes. Even though the positioning accuracy of GPS or other automatic systems is approximate, they provide good support and background information. More accurate localisation can later be done by photogrammetric means.

In the FJHP, the creation of a functional geospatial photo archive still remains a challenge. The 3D virtual geographic model, a frame in which all the archaeological data and interpretation would be projected and visualized, is our scheme to transform all the acquired data to a one consistent coordinate system and interface. Spatial aspects of archaeological databases have been studied in several projects (e.g. Reilly, 1989; Lavah Research Project, 1999; Vote, 2001; Cosmas *et al.* 2001; Learning Sites, 2002; Drap *et al.*, 2006), and it has been shown that spatial database

offers an archaeologist a better understanding of the record compared to traditional on-site methods alone (Vote, 2001: 94-98). Exploiting the human ability to interpret visual data, the scientific visualization can increase deeper comprehension of the data and bring new insight into the underlying processes (Earnshaw, 1992: 1). 3D GIS have been tested in archaeological uses (e.g. Doneus and Neubauer, 2005; Nebiker and Wüst, 2006; Drap *et al.,* 2006: 70-72; Conolly and Lake, 2006: 38-39), and virtual reality as interface for scientific databases has been examined (e.g. Johnson and Fotouhi, 1994; van Maren and Germs, 1999; Vote, 2001: 46-66; Webb and Brotherhood, 2002; Earl and Wheatley, 2002; Stricker *et al.,* 2006: 432). However, the existing solutions commonly suffer from e.g. problems of interaction, integration of different data, completeness, 3D nature of the data, or accuracy.

4.4.3 Archaeological Interpretations on the Image Prints

To measure archaeological entities and visualize 3D models with archaeological interpretations, interpretations of the scene have been drawn on image prints on site (Fig. 34). Image prints compared to digital drawing are preferable for two reasons: they are faster and they can equally be used for measuring and modeling purposes as e.g. orthophotos. In practice, these prints have been used as a part of the 3D modeling process, in which drawings have been measured as 3D coordinates. These interpretations are important to complete on site, since stone-by-stone interpretation becomes difficult if it is done from images after the excavation phase. Likewise, the stereo images facilitate interpretations done in the future.

Figure 34. Some archaeological interpretations drawn on an image print. Every locus or interesting feature of this excavation phase has been interpreted with the corresponding locus number on the image print.

4.4.4 Definition of the Coordinate System on the Scene

Control points or features are necessary for transforming the field data, photographs and 3D models into the common geographic reference system. It was important to understand the most convenient way to signalize the control points in a manner that they are visible on images. At the beginning, the control points were marked in different ways, such as with water bottle caps (Fig. 35a). The exact position of the marker was then measured with the tacheometer usually after the photographs were taken. The method proved to be rather cumbersome in practice, and eventually, it was most productive to use natural control points (Fig. 35b). This method made certain that the control points were always visible on photographs and since the physical signals tended to move during the excavations, the natural control points proved to be more accurate in the end (Koistinen, 2004). Also features, such as building structures measured by tacheometer, can be used in geo-referencing.

However, interactive feature-based orientation software (Rönnholm *et al.*, 2003) needs to be applied then. (Junnilainen *et al.*, 2007.)

Figures 35 a-b. Artificial control point (a) and natural control point (b). The control points were measured by tacheometer. (FJHP/Nina Heiska and Hanne Junnilainen)

Control points should be located extensively on the model area and preferably, not in the same spatial plane. We established at least 4-5 points per each model. Control points, which can also be used to orient adjacent models, e.g. neighbouring trenches or successive models of the excavation process, are advantageous. Points for subsequent models can also be attained by photogrammetric means. In that case, previously georeferenced models or images can be used to obtain extra tie points.

4.4.5 Measurement of Corresponding Points on Image Coordinate System

Corresponding image points are measured to obtain orientations of the images and to acquire suitable points for the 3D model. In order to achieve a geometrically strong image block for the bundle block adjustment and base for the modeling, points for the image orientations are collected first. This means points that are clear, are seen from different angles and are spread extensively on an image area. Secondly, points that represent the scene of the model are measured. If modeling is started before strong image block is achieved, unclear modeling points might cause non-solvable orientations or slower the process. In the end, a 3D model is geo-referenced with the known control points. (Fig. 36)

Figure 36. Corresponding image points are measured and topology is defined on image coordinate system (upper left and right). Wire-frame model (lower left) and photo-textured model (lower right) are produced according to the point and topology information. (FJHP/Anna Erving and Karolina Fieber)

It was quickly noted that the straight recognition of the corresponding points from the strongly convergent image pair was difficult, since the stones resembles more of a ball than a geometrically formed cube. Therefore, it was important to notice that the point or the feature can be ´followed´ by images taking from the slightly different angles and the convergent configuration can be obtained by following these image 'sequences' (Fig. 37).

60
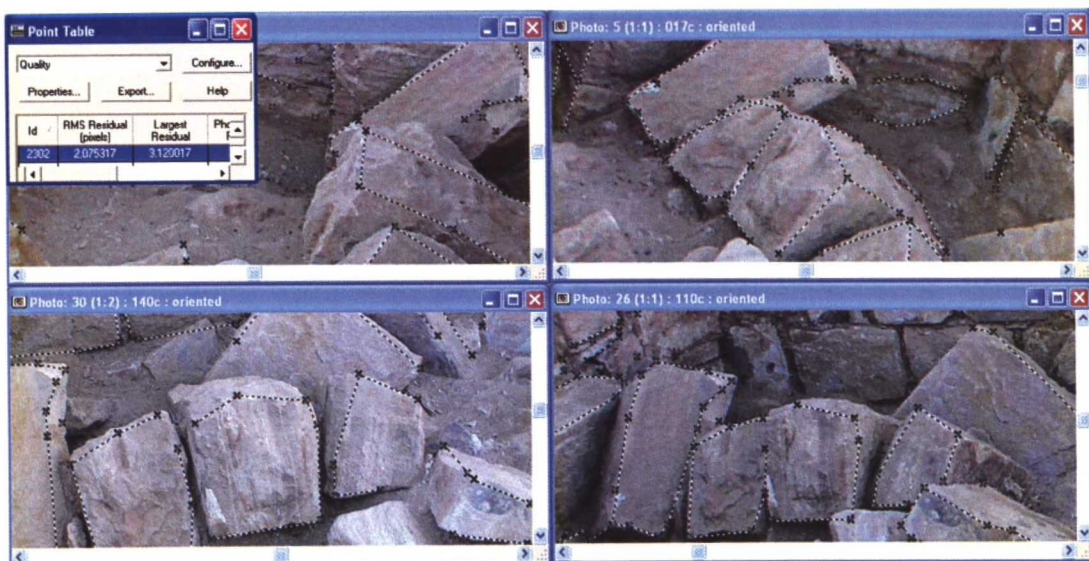
Figure 37. The recognition of the corresponding points is sometimes difficult from the strongly convergent image pair. The points and features can be ´followed´ from the images taken from the slightly different angles and in the end, the accurate measurement can be completed with the convergent geometry. Residuals of the each point can also be observed simultaneously.

The measurement of the points is the most time consuming stage of the modeling. In the case of geometrically unformed close-range scenes, convergent camera axes and wide baseline will develop and therefore, strong differences will exist in corresponding image parts. Consequently, automatic recognition of corresponding points is problematical. Video imaging has potential capability in automate feature extraction (e.g. Fitzgibbon and Zisserman, 1998; Nistér, 2004; Pollefeys *et al.,* 2004), but methods have not been that successful or proven in practical applications (Remondino and El-Hakim, 2006: 273). Supporting assumptions of the object shape (e.g. Debevec *et al.,* 1996; Dorffner and Forkert, 1998; Dick *et al.,* 2000; Werner and Zisserman, 2002), e.g. perpendicularity of the walls, cannot either be used in FJHP as scenes are unformed. Terrestrial laser scanning could partially solve the problem of automatic 3D measuring, but is expensive and the conditions of Jabal Haroun restrict the use of the complex electronic equipment. As a semi-automatic option, retro signals offered by *PhotoModeler Pro* could save time during the image orientation stage (PhotoModeler Pro, 2004: 483, 359-368). For all these reasons, our research emphasis has been put on semi-automated or interactive methods.

4.4.6 Calculation of the Image Orientations

The image orientations were performed successfully in the *PhotoModeler Pro*. As an input for the bundle block adjustment, information about camera calibration (Fig. 38), corresponding image points and control points are needed. Also the directions of the different coordinate systems need to be considered, e.g. left-handed UTM coordinates have been transformed to right-handed *PhotoModeler* coordinate system by changing the places of x and y axes.

Figure 38. In the *PhotoModeler Pro 5*, the parameters of interior orientation are given for each camera used. The parameters of the lens distortion (K1, K2, K3, P1 and P2) are correspondent to the parameters described in the Chapter 3.3.1.

During the orientation stage of the images, the point marking residual of each point was kept under three pixels. When modeling points were marked, the residuals evidently become larger. The statistics of each 3D model are presented in table 5. In our case, the large RMS values are mainly caused by the geometrically unformed objects. In general, the results achieved by *PhotoModeler* are promising: coordinate accuracies from 1:8000 (with natural control points) to 1:10 000 (with retro-reflective signals) have obtained (Hanke, 2001; Fedak, n.d.). For distance measurements, accuracy of 1:6500 with the calibrated off-the-self digital camera, natural control points and constant focus setting have been accomplished (Hanke, 2001). Considering the accuracy of a 3D model in general, the excavation scene is

typically geometrically unformed, and therefore, the 3D models can be seen merely approximated presentation of the object than an exact replica. Above all, the desired accuracy and level of details need to be defined according to the case and it can vary within a model.

Table 5. The statistics of each 3D model.

Model	Modelling Images	Points	Overall RMS of Point Marking Residual (pixels)	Avg. Rays per Point	Avg. Angle Intersection (deg.)	Point Coverage on Photo (%area)
Chapel	47	1526	3.747	5	55	59
Church nave	68	1117	6.278	5	66	64
Church apsis	32	988	5.967	3	59	73
Trench A1	102	5365	3.371	4	50	64
Mosaic floor	19	504	1.437	3	47	59

4.4.7 Definition of Topological Information

Besides the point measurements, surfaces of the model need to be described. Polygons are generally the most flexible way to approximate the surfaces of the object. Surfaces must be defined in a way that they approximate the real scene adequately. If there are gross errors, coarseness or incorrectly directed surfaces in a geometrical model, they will probably become evident when projecting the texture onto the object shape. In our case, the topology is fixed both for geometrical model and for archaeological interpretations.

In figure 36, the topology has been fixed manually as polygons. However, in the cases of objects like statues or denser point clouds, topology can also be defined by automate triangulation, as in the case of mosaic floor (Figs. 39 a-c). More detailed ideas of the automate surface generation can be found from Edelsbrunner (2001), and Remondino and El-Hakim (2006).
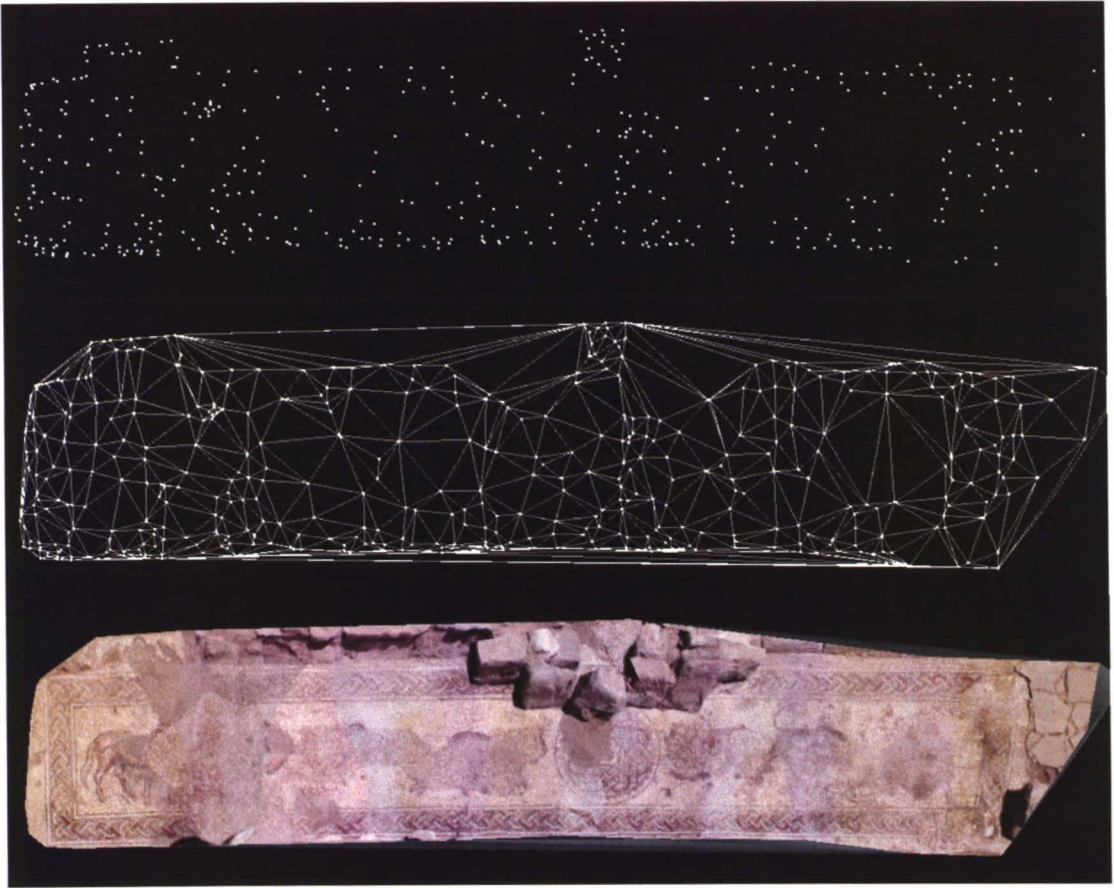
Figures 39 a-c. Orthophoto production of a mosaic floor: measurement of the corresponding points (a), definition of the topology (b), and texturing (c). In this case, the definition of the topology and the texturing were done automatically.

4.4.8 Texturing

The radiometrical model is created by texturing a geometrical model. Texturing or texture mapping means adding of a surface texture to a two-dimensional face or polygon of a 3D model (Heckbert, 1989; Weinhaus and Devarajan, 1997; Weinhaus and Devich, 1999). Surface texture a.k.a. texel can be single colour, artificial pattern or a real photograph. Texture mapping increases the realism and data content of the geometrical model (Figs. 40 a-b).

In photo-textured models, real photographs are used as a texture. In this way, photo-textured models can be distinguished from photo-realistic models in which texture contents are artificially created. In the FJHP approach, photo-texture is manually
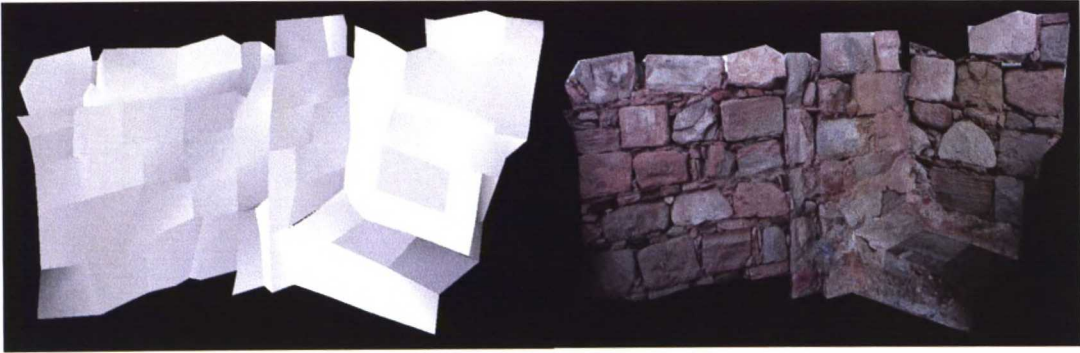
Figure 40 a-b. A shaded 3D model (a) and a photo-textured 3D model (b) of the same target. The photo-texture increases the data content and realism of the 3D models. (FJHP/Karolina Fieber and Hanne Junnilainen)

created for each polygon. As textured images are also used for geometrical modeling, their interior and exterior orientation is already defined prior to texturing. The decision, which photograph is the most suitable for texture, is mainly done automatically based on the criteria of orthogonality and resolution. However, after visual inspection, some texture photographs were chosen manually. On the other hand, in the case of mosaic floor, texturing of the triangular model was done completely automatically (Fig. 39c).

4.4.9 Post-Processing and Visualization

The post-processing and visualizations work of the 3D models is still under way. Orthophotos have been produced from the photo-textured 3D models (Fig. 39 a-c), and archaeological interpretations of the loci have been visualized on top of the 3D models (Figs. 41 a-b). During the work, several new post-processing and visualization possibilities were thought out for the end products and part of them are listed in table 6.

Table 6. Post-processing and visualizations possibilities for 3D models in archaeological applications.

Process	End Product	Use
3D modeling	A 3D model of an entity, e.g. trench model	- Ortho-photo production (Fig. 23) - Dimensional drawing on top of the photo-textured 3D model - Archeological interpretations on top of the 3D model (Col. Fig. 9a-b) - Monitoring the change - Planning and documentation of conservation - Measurements - Visualizations for the media - Animations
Merging of adjacent models, e.g. trench models	Spatially extensive excavation 3D model	- Spatial and temporal analysis
Merging of models in different scales, e.g. artefact model, environmental model	Multi-scale 3D model	- Spatial and temporal analysis
Merging of successive models of excavation phases	Multi-temporal 4D model	- Calculation of cross sections along arbitrary defined lines - Calculation of volumes of deposits - Merging of structures from the different phases of the excavation and understanding the changes - Animations
3D/4D models connected to database, e.g. images, finds, text, sounds, tacheometer data	3D/4D information system	- Analysis - Popularized products of an archaeological research, e.g. educational material, computer games - Comparison and fusion of different data
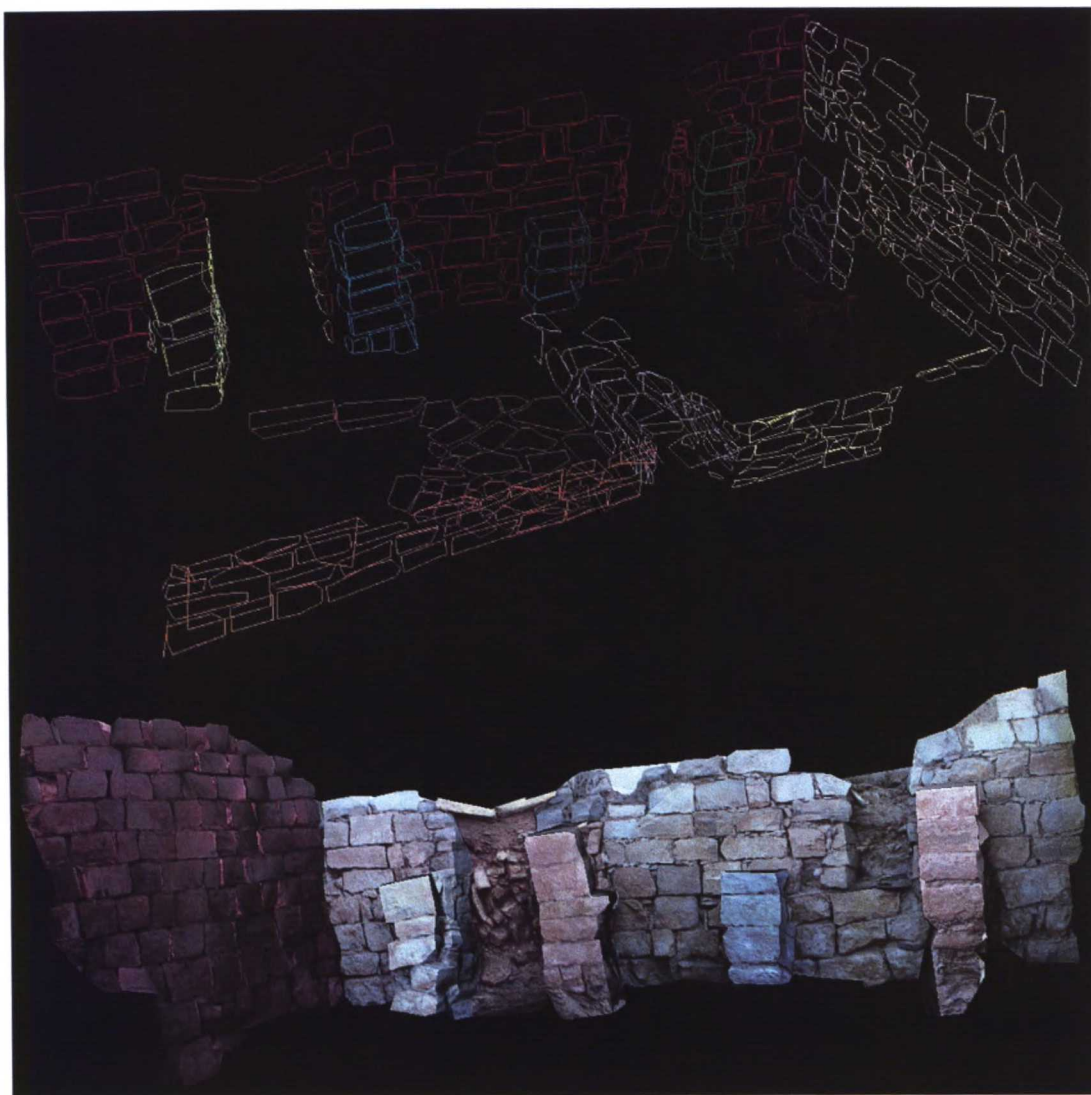
Figures 41 a-b. 3D models with the archaeological interpretations. The 3D model is measured stone-by-stone, and each locus is represented with different colour (a). Each locus is symbolized with different colours on the top of the photo-textured 3D model (b).

Chapter 5

Discussion

In this chapter, the practical aspects of planning and realization of the photogrammetric documentation of archaeological excavation work are discussed. Proposals are presented about the following subjects: planning of the fieldwork, mapping of the environment, establishment of the consistent coordinate frame, database and improvements for the 3D modeling process.

Since the photogrammetric documentation of the cultural heritage has been researched comprehensively, it is recommended to get acquainted with work experiences of others. The documentation of the archaeological process is in many ways challenging and practical problems arise constantly since the settings are far from the laboratory conditions. Additionally, attention must be paid on the maintenance of the infrastructure, e.g. supply of the electricity and backups of each procedure.

From the post-excavation work perspective, it is important to remember that the recording and operational work of the data is so time consuming that also sufficient resources for the post field season activities and research should be reserved. If the fieldwork runs for one month, at least three months for the post work is needed – and that is easily an underestimation. At the same time, decisions about the accuracies and levels of details need to be done. In an excavation, the documentation is after all an endless process and significance of each case need to be decided carefully.

Also the multidisciplinary expertise and collaboration is required. For example, from the technical point of view, knowledge of land-surveying, photogrammetry, cartography, database management, GIS, Virtual Reality and Web technologies is

valuable. In the case of FJHP, e.g. the land-surveying and cartographic activities have occupied the staff considerably compared to the focus of their photogrammetric research work. Above all, to make the interdisciplinary work productive, the exchange of ideas between the specialists should be valued.

As the surroundings of the site are of interest for the archaeologist, the mapping of the larger environment should be emphasized. Especially, photo-textured DEMs visualize the environment in a way that it is easy to comprehend it as a whole. In the creation of general 3D model of the whole site, aerial oblique images or broad view terrestrial images are particularly valuable. Moreover, the mapping of the surroundings can also be seen as groundwork of the fieldwork, because it can serve as a tool for the archaeological planning, e.g. survey of the related sites or roads or relocation of the excavated material. Particularly, this is important in the planning of the control point network, since the area of investigation can be defined more precisely. It is important to build the control point network extensively from the beginning, because then the accuracy and consistency remains higher. The informative document of the control point network also makes the future documentation work considerably more efficient.

The planning, development and maintenance of a functional database for the archaeological project cannot be underestimated. Excavations are after all long-lasting projects and therefore, the amount and variety of the data can be considerable. As the archaeological data is multi-scale, multi-resolution and multi-sensor in its nature, the storing and relations of the information are challenge to the data management. During the long projects, the data formats and operating systems are probably changing as well. From the respect of the data quantity, it is also important to enable the acquisition of additional material, because it can be used for different applications and research questions in the future. In the organisational level, the functional database is the foundation for the availability of the research data, the interdisciplinary discussion between the researchers and the distribution of the results for the public and sponsors.

Particularly, the photography is hard to manage in a functional manner. In the FJHP, the creation of a geospatial photo archive still remains a challenge. Currently all the

images are indexed according to their attribute content. As soon as both the 3D geographic model and respective georeference of the images are known, the browsing of images should be based on geographic pointing. Automatic system for collecting the position and angle of bearing of imaging would facilitate the process. Even approximate georeference information will be useful for preliminary data search, since the accuracy of the georeference increases then automatically along the progress of 3D modeling. In fact, the 3D model, is our scheme to transform all the acquired data to a one consistent coordinate system and interface. (Junnilainen *et al.* 2007.)

From the 3D modeling perspective, the automation of the process remains a complicated and important research question. At the moment, the measurement of the corresponding points is the most time consuming stage of the modeling. However, a totally automate solution is probably far in the future and therefore, our research emphasis has been put on semi-automated or interactive methods. In the image-based modeling, the targets that can be easily arranged and removed might help the semi-automation of the image orientation.

If possible, the use of laser scanning would fasten the creation of a digital surface model. Then, the archaeological interpretations could be measured simply by single image approach i.e. monoplotting technique – however, the orientation of the images needs to be known then. Additionally, images would serve as a source of texture information. The comparison of laser scanning and photogrammetry as documention methods can be found from Böhler (2006).

In FJHP, the photogrammetric and tacheometer documentation of the excavation have been overlapping. The importance of the tacheometer measurements lies in the real-time measurements, localisation of the finds and geo-reference for the images. Other than that, the documentation could be done solely by photogrammetric means and time for the 3D modeling would be saved.

Chapter 6

Conclusions

Photogrammetry has been widely used in the documentation of cultural heritage and general guidelines of the documentation have been developed by international organisations. However, the guidelines are describing the problem in general level and therefore, the practical implementation of the heritage documentation is lacking instructions, specifications and policies. Additionally, no single method can be applied to diversity of all the archaeological objects. Therefore, the choosing of technology (sensor, hardware and software), procedures, needed level of detail, planning of the workflow and quality assurance in the end is still problematic and the field seems to be disorganised in it. At the same time, new methodologies are developing and they are on one hand, amplifying the possibilities, but on the other hand, increasing the confusion and used practices.

In the excavations of Finnish Jabal Haroun Project, variety of photogrammetric and geodetic methods has been applied throughout the years. The most practical working routines, methods, experiences and other observations are presented in the case study of this thesis. The data, processes, products, archive, uses of the products and future needs are described and compiled into a flow chart (Fig. 16). The second objective of this thesis – to examine and test the 3D modeling in the excavation process – has also been presented in the case study and collated into the flow chart of the 3D modeling (Fig. 26). In fact, the developed 3D modeling process is our proposal of the practical photogrammetric concept to be used in the archaeological documentation.

Some of the broader photogrammetric research objectives of the FJHP project have been achieved through this study. The first objective of the FJHP has been to

71

produce a virtual geographic model of the excavations at Jabal Haroun. This aim has not yet been reached, but as a prerequisite, the 3D modeling process has now been tested. The second photogrammetric objective of the project was to develop useful photogrammetric concepts for the archaeological documentation and to obtain the data in a way that the images can be applied with different research questions in the future. This aim has been reached and the unique raw material, the photographs, has been acquired. Additionally, the basic tacheometer documentation of the excavation has been completed and therefore, the material to support the archaeological research is available.

At this point, the 3D modeling has been tested in four cases, i.e. the chapel, church, trench A1, and the mosaic floor of the narthex. The consumer-grade digital cameras and commercial photogrammetric software, *PhotoModeler Pro 5*, has been employed. The process consists of image acquisition and the production of the 3D model using these images. The images were oriented with the block adjustment method and geo-referenced by natural control points. 3D interpretation of the object was done manually and supported by the sketches produced during the archaeological fieldwork. The resulting 3D models are regarded to be the frame in which all the data can be projected.

The advantages of the photogrammetry as an archaeological documentation method proved to be the fast image acquisition, non-interpreted nature of the images, texture and the fact that vast amount of data can be obtained in various scales. Also the photo-textured 3D models proved to be a realistic and accurate tool for the archaeological documentation and analysis. 3D models visualize the features efficiently, but the models can also later provide additional information, e.g. previously unnoticed details and new interpretational possibilities. However, the post-processing of photogrammetric modeling is time-consuming, since the automatic recognition of corresponding points remains difficult. So far, commercial photogrammetric applications capable of totally automatic modeling do not exist.

The use of the original image prints as documentation frames for archaeological recording was regarded as an innovative concept. It considerably reduces the time needed for the documentation, as there is no need to produce dimensional drawings

or orthophotos. Subsequently, the sketches can be converted into the used coordinates system during the process of 3D modeling. Orthophotos are needed as a drawing reference only in the cases, where some measurements need to be done on site because the all the details may not be visible on images.

From the perspective of the photogrammetric science, the work in the FJHP has generated a new research problem of ´multi-scale and multi-temporal photogrammetric georeferencing´. The task is to transform diverse data into one consistent coordinate frame. At the moment, vertical and oblique aerial images, satellite images, terrestrial photographs, tacheometer data and maps of the FJHP survey area are examined in this purpose.

REFERENCES:

Aguilera D.G., J.G. Laboz, J. Finat, J. Martinez, J. Fernández, and J. San Jose, 2006. Terrestrial Laser Scanning and Low-Cost Aerial Photogrammetry in the Archaeological Modeling of a Jewish Tanniers. *Proceedings of the ISPRS Commission V Symposium "Image Engineering and Vision Metrology"*, Volume XXXVI, Part 5, pp. 8-13.

Allen, P. K., I. Stamos, A. Troccoli, B. Smith, M. Leordeanu, Y.C. Hsu, 2003. 3D Modelling of Historic Sites Using Range and Image Data. *International Conference of Robotics and Automation*, September 2003, Taipei, Taiwan, pp. 145-150.

Atkinson, K.B. (ed.)
1996 *Close Range Photogrammetry and Machine Vision.* Bristol: Whittles Publishing. 371 p.

Balletti, C., F. Guerra, P. Vernier, N. Studnicka, J. Riegl, and S. Orlandini, 2004. Practical Comparative Evaluation of an Integrated Hybrid Sensor Based on Photogrammetry and Laser Scanning for Architectural Representation. *International Archives of Photogrammetry and Remote Sensing*, Volume 35, Issue 5, pp. 536-541.

Balletti, C., F. Guearra, A. Lingua, F. Rinaudo, 2005. True Orthophoto of the San Marco Basilica in Venice. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Science*, Volume 34, Part 5/W12, pp. 43-48.

Bannister, A., S. Raymond, and R. Baker, 1998. *Surveying,* Seventh edition. Harlow and London: Pearson and Prentice Hall. 512 p.

Bernardini F., H. Rushmeier, I. M. Martin, J. Mittleman, and G. Taubin, 2002. Building a Digital Model of Michelangelo's Florentine Pieta. *IEEE Computer Graphics and Applications*, Volume 22, Issue 1, pp. 59-67.

Burke, H. and C. Smith, 2004. *The Archaeologist's Field Handbook.* Crows Nest: Allen & Unwin. 406 p.

Bujakiewicz, A., M. Kowalczyk, P. Podlasiak, and D. Zawieska, 2006. 3D Reconstruction and Modeling of the Contact Surfaces from the Archaeological Small Museum Pieces. *ISPRS Comission V Symposium "Image Engineering and Vision Metrology"* , Volume XXXVI, Part 5, pp. 56-61.

Böhler, W., 2006. Comparison of 3D Laser scanning and other 3D Measurement Techniques. In: *Recording, Modeling and Visualization of Cultural Heritage.* Eds: E. Baltsavias, A. Gruen, L. Van Gool, and M. Pateraki. London: Taylor & Francis Group. Pp. 89-99.

CIPA, 2007. Home page of International Committee for Heritage Documentation. http://cipa.icomos.org/

Conolly, J., and M. Lake, 2006. *Geographical Information Systems in Archaeology.* Cambridge: Cambridge University Press. 338 p.

Cosmas, J., T. Itegaki, D. Green, E. Grabczewski, F. Weimer, L. Van Gool, A. Zalesny, D. Vanrintel, F. Leberl, M. Grabner, K. Schindler, K. Karner, M. Gervautz, S. Hynst, M. Waelkens, M. Pollefeys, R. DeGeest, R. Sablatnig, and M. Kampel, 2001. 3D MURALE: A Multimedia System for Archaeology. *Proceedings of the 2001 Conference on Virtual Reality, Archaeology, and Cultural Heritage,* Glyfada, Greece, pp. 297-305.

Cooper, M.A.R. and S. Robson, 1996. Theory of close range photogrammetry. In: *Close Range Photogrammetry and Machine Vision.* Ed: K.B. Atkinson. Bristol: Whittles Publishing. Pp. 9-51.

D'Ayala, D. and P. Smars, 2003. Minimum requirement for metric use of non-metric photographic documentation, Univerisity of Bath Report. http://www.english-heritage.org.uk/server/show/conWebDoc.4274 (31 May 2007)

Debevec, P., C. Taylor, and J. Malik, 1996. Modelling and Rendering Architecture from Photographs: A Hybrid, Geometry- and Image-based Approach. *Conference Proceedings of SIGGRAPH 1996,* New Orleans, Louisiana, pp.11-20.

Dick, A., P. Torr, and R. Cipolla, 2000. Automatic 3D Modelling of Architecture. *Electronic Proceedings of the Eleventh British Machine Vision Conference.* http://www.bmva.ac.uk/bmvc/2000/papers/p38.pdf (29 March 2007)

Doneus, M., W. Neubauer, and N. Studicka, 2003. Digital Recording of Stratigraphical Excavations. *XIXth CIPA International Symposium 2003.* Antalya, Turkey.

Doneus, M., and W. Neubauer, 2005. 3D Laser Scanners of Archaeological Excavation. *Proceedings of the CIPA 2005 XX International Symposium,* Torino, Italy, pp. 226-231.

Dorffner L., and G. Forkert, 1998. Generation and Visualization of 3D Photo-Models Using Hybrid Block Adjustment with Assumptions on the Object Shape. *ISPRS Journal of Photogrammetry and Remote Sensing,* Volume 53, Issue 6, pp. 369-378.

Drap, P., A. Durand, M. Nedir, J. Seinturier, O. Panini, F. Boucault, P. Chapman, W. Viant, G. Vannini, M. Nuccioti, 2006. Towards a Photogrammetry and Virtual Reality Based Heritage Information System: A Case Study of Shawbak Castle in Jordan. *The 7th International Symposium on Virtual Reality, Archaeology and Cultural Heritage,* VAST (2006), Cyprus, pp. 67-74.

Earl, G. and D. Wheatley, 2002. Virtual Reconstruction and the Interpretative Process: A Case-study from Avebury. Pp. 5-15 in: *Contemporary Themes in Archaeological Computing.* Eds: D. Wheatley, G. Earl, and S. Poppy. Oxford: Oxbow Books.

http://eprints.soton.ac.uk/28768/ (28 March 2007)

Earnshaw, R., 1992. Introduction. Pp. 3-13 in: *Scientific Visualization, Techniques and Applications.* Eds: K. W. Brodlie, L. A. Carpenter, R. A. Earnshaw, J. R. Gallop, R. J. Hubbold, A. M. Mumford, C. D. Osland, and P. Quarendon. Berlin, Heidelberg: Springer-Verlag. 284 p.

Edelsbrunner, H., 2001. *Geometry and Topology for Mesh Generation.* Cambridge Monographs on Applied and Computational Mathematics, No. 7. Cambridge: Cambridge University Press. 190 p.

Fedak, M., n.d. Measurement Accuracy of a Consumer-Grade Digital Camera and Retro-Reflective Survey Targets. Eos Systems Inc.
http://www.photomodeler.com/products/photomodeler/documents/fedak1.pdf
(9 February 2007)

Ferwerda, J. G., 1987. *The World of 3-D, A Practical Guide to Stereo Photography,* second edition. Borger: 3-D Book Productions. 300 p.

Fiema, Z., C. Danielle, J. Frösén, A. Erving, H. Haggrén, N. Heiska, R. Holmgren, V. Homqvist, H. Junnilainen, K. Koistinen, A. Lahelma, J. Latikka, A., Lehtinen, J. Lindblom, P. Miettunen, E. Mikkola, S. Pouta, S. Schmidt *et al.,* **2007.** The Final Publication of FJHP, Volume 1. In the press.

Fitzgibbon, A., and A. Zisserman, 1998. Automatic 3D Model Acquisition and Generation of New Images from Video Sequence. *Proceedings of the European Signal Processing Conference,* Rhodes, Greece, Pp. 1261-1269.

Fraser, C. S., 1996. Network Design. In: *Close Range Photogrammetry and Machine Vision.* K.B. Atkinson, ed. Bristol: Whittles Publishing. Pp. 256-281.

Fryer, J. G., 1996. Camera Calibration. In: *Close Range Photogrammetry and Machine Vision.* Ed: K.B. Atkinson. Bristol: Whittles Publishing. Pp. 156-179.

Frösén, J., Z. T. Fiema, H. Haggrén, K. Koistinen, M. Lavento, and G. Peterman, 1998. The Finnish Jabal Haroun Project, Report on the 1997 Season. *Annual of the Department of Antiquities of Jordan* (ADAJ) 42, pp. 483-502.

Gaisecker, T., 2006. Pinchango Alto – 3D Archaeology Documentation using the Hybrid 3D Laser Scan System of RIEGL. In: *Recording, Modeling and Visualization of Cultural Heritage.* Eds: E. Baltsavias, A. Gruen, L. Van Gool, and M. Pateraki. London: Taylor & Francis Group. Pp. 459-464.

Gemenetzis, D., H. Georgiadis, P. Theoharidis, P. Patias, 2001. Virtuality and Documentation: Recreating The Byzantine Heritage. *International Archives of Photogrammetry and Remote Sensing,* Volume 34, Part 5/W1, pp. 159-164.

Georgiadis, C., V. Tsioukas, L. Sechidis, E. Stylianidis, and P. Patias, 2000. Fast and Accurate Documentation of Archaeological Sites Using In The Field

Photogrammetric Techniques. *CD of ISPRS XIX Congress*, Supplement B5, 16-22 July, Amsterdam.

GeoSpatial Experts, 2006. GeoSpatial Experts www-page.
http://www.geospatialexperts.com/ (9 February 2007)

Gonzo, L., S. El-Hakim, M. Picard, S. Girardi, E. Whiting, 2004. Photo-Realistic 3D Reconstruction of Castles with Multiple-Sources Image-Based Techniques. *Proceedings of the International Society for Photogrammetry and Remote Sensing (ISPRS) XXth Congress*, Istanbul, Turkey, pp. 120-125.

Gruen A., F. Remondino, L. Zhang, 2004. Photogrammetric Reconstruction of the Great Buddha of Bamiyan, Afghanistan. *The Photogrammetric Record*, Volume 19, Issue 107, Pp. 177-199.

Gruen, A., F. Remondino, and L. Zhang, 2006. The Bamiyan project: multi-resolution image-based modeling. In: *Recording, Modeling and Visualization of Cultural Heritage*. Eds: E. Baltsavias, A. Gruen, L. Van Gool, and M. Pateraki. London: Taylor & Francis Group. Pp. 45-53

Guarnieri, A., A. Vettorea, S. El-Hakim, and L. Gonzo, 2004. Digital Photogrammetry and Laser Scanning in Cultural Heritage Survey. *Proceedings of the International Society for Photogrammetry and Remote Sensing* (ISPRS) *XXth Congress*, Istanbul, Turkey, pp. 154-158.

Haala, N., and Y. Alshawabkeh, 2006. Combining Laser Scanning and Photogrammetry – A Hybrid Approach for Heritage Documentation. *The International Symposium in Virtual Reality, Archaeology and Cultural Heritage*, VAST (2006), Cyprus, pp. 163-170.

Haggrén, H., P. Pöntinen, and J. Mononen, 1998. Concentric Image Capture for Photogrammetric Triangulation and Mapping and for Panoramic Visualization. *Videometrics VI, SPIE Proceedings*, Volume 3641, pp. 17-21.

Haggren, H., 2001. *Luento 1: Erikoissovellusten päätehtävät*. Lecture of Maa-57-260 Close-Range Photogrammetry, Institute of Photogrammetry and Remote Sensing, Helsinki University of Technology.
http://foto.hut.fi/opetus/260/luennot/1/1.html (18 May 2007)

Haggrén, H., 2002. *Luento 3: Kolmiointihavainnot*. Lecture of Maa-57.220 Photogrammetric Mapping course, Instute of Photogrammetry and Remote Sensing, Helsinki University of Technology.
http://foto.hut.fi/opetus/220/luennot/3/3.html (25 May 2007)

Haggrén, H., H. Hyyppä, O. Jokinen, A. Kukko, M. Nuikka, T. Pitkänen, P. Pöntinen, and P. Rönnholm, 2004a. Photogrammetric application of spherical imaging. ISPRS Panoramic Photogrammetry Workshop. Dresden, Germany.
http://www.commission5.isprs.org/wg1/workshop_pano/papers/PanoWS_Dresden2004_Haggren.pdf (23 April 2007)

Haggrén, H., H. Junnilainen, J. Järvinen, and T. Nuutinen, 2004b. The Use of Panoramic Images for 3-D Archaeological Survey. *Proceedings of the International Society for Photogrammetry and Remote Sensing (ISPRS) XXth Congress*, Istanbul, Turkey, pp. 958-963.

Hanke, K., 2001. Accuracy Study Project of Eos Systems' PhotoModeler, Final Report.
http://www.photomodeler.com/products/photomodeler/documents/hanke.pdf   (3 April 2007)

Harris, E. C., 1989. *Principles of archaeological stratigraphy*, 2nd edition. London: Academic Press. 170 p.

Heckbert, P. S., 1989. *Fundamentals of Texture Mapping and Image Warping*. Master's Thesis, Department of Electrical Engineering and Computer Science, University of California, Berkeley, USA, 86 p.
http://www.cs.cmu.edu/~ph/texfund/texfund.pdf (14 March 2007)

Honkanen, P., 1999. *Taso- ja korkeus lähtöpisteistön suunnittelu ja mittaaminen Finnish Jabal Haroun projektille.* Unpublished Bachelor's Thesis. Espoo and Vantaa University of Applied Science (EVTEK), Study Program of Surveying. Vantaa. 39 p.

ICOMOS Charters, 2007. International Charters for Conservation and Restoration.
http://www.international.icomos.org/charters/charters.pdf

Ioannidis, C., P. Pappa, S. Soile, E. Tsiliggiris, A. Georgopoulos, 2001. Orthophoto Production Comparison Test for Close-Range Applications in Highly Curved Objects. *XVIII International Symposium CIPA 2001*, 18.-21.9.2001, Potsdam, Germany.

iWitness, 2007. iWitness software www-page.
http://www.iwitnessphoto.com/ (9 March 2007)

Johnson, A., and F. Fotouhi, 1994. The SANDBOX: a Virtual Reality Interface to Scientific Databases. *Proceedings of the Seventh International Working Conference on Scientific and Statistical Database Management*, Charlottesville, Virginia, Pp. 12-21.

Junnilainen, H., K. Koistinen, J. Latikka, H. Haggrén, A. Erving, and N. Heiska, 2007. The Cartographic Documentation in the FJHP Excavations. In: The Final Publication of FJHP, Volume 1. Ed: Z. Fiema. In the press.

Kahmen, H., and W. Faig, 1988. *Surveying*. Berlin: Walter de Gruyter & Co. 578 p.

Karras, G., P. Patias, and E. Petsa, 1996. Monoplotting and Photo-unwrapping of Developable Surfaces in Architectural Photogrammetry. *International Archives of Photogrammetry and Remote Sensing*, Volume 31, Issue 5, pp. 290-294.

Koistinen, K., J. Latikka, and P. Pöntinen, 2001. The Cumulative 3D Data Collection and Management During An Archaeological Project. *XVIII International Symposium CIPA 2001*, Potsdam, Germany, pp. 223-228.

Koistinen, K., 2004. Multitemporal Archaeological Imagery to Model the Progress of Excavation. *Proceedings of the International Society for Photogrammetry and Remote Sensing* (ISPRS) *XXth Congress*, Istanbul, Turkey, pp. 1006-1012.

Konecny, G., 1985. The International Society for Photogrammetry and Remote Sensing - 75 years old, or 75 years young. *Photogrammetric Engineering and Remote Sensing*, Volume 51, Issue 7, pp. 919-933.

Kraus, K., 1993. *Photogrammetry*, Volume 1, Fundamentals and Standard Processes, 4th edition. Bonn: Dümmlers Verlag. 397 p.

Kraus, K. 1997. *Photogrammetry*, Volume 2, Advanced Methods and Applications, 4th edition. Bonn: Dümmlers Verlag. 466 p.

Kukko, A., 2001. *Digitaalikameran asemointi pallopanoraama-alustaan.* Special Assignment, Department of Surveying, Helsinki University of Technology. 20 p.

La Pensée, A. A., M. I. Cooper, and J. B. Parsons, 2006. Applications in the Field of cultural Heritage using "off-the-self" 3d Laser Scanning Technology in Novel ways. *The 7th International Symposium on Virtual Reality, Archaeology and Cultural Heritage* VAST (2006), Cyprus, pp. 217-221.

Lavah Research Project, 1999. Excavation in Israel, Lavah Research Project at Tell Halif, http://www.cobb.msstate.edu/dig/LRP-1999-01/visualization.html (15 February 2007)

Lavento, M., E. Hertell, P. Kouki, A. Mukkala, S. Silvonen, H. Ynnilä, H. Haggrén, H. Junnilainen, A. Erving, 2006. The Finnish Jabal Haroun Project Survey: Preliminary Results from Six Seasons of Archaeological Fieldwork in Jordan. *Proceedings of the Finnish Institute of the Middle East* 1/2006, Vantaa. 39 pp.

Learning Sites, 2002. Learning Sites Inc.
http://www.learningsites.com/ (15 February 2007)

Lianos, N., S. Spatalas, V. Tsioukas, and E. Gounari, 2004. 3D Modeling of the Old Town of Xanthi in Greece. *Proceedings of the International Society for Photogrammetry and Remote Sensing (ISPRS) XXth Congress*, Istanbul, Turkey, pp. 542-545.

Liebowitz, D., A. Criminisi, and A. Zisserman, 1999. Creating Architectural Models from Images. *Computer Graphics Forum*, Volume 18, Number 3, pp. 39-50.

Lingua, A., F. Rinaudo, G. Auditore, C. Balletti, F. Guerra, L. Pilot, 2003. Comparison of surveys of St. Mark's square, in Venice. *XIXth CIPA International Symposium 2003.* Antalya, Turkey.

http://cipa.icomos.org/fileadmin/papers/antalya/71.pdf (6 March 2007)

Luhmann, T., and W. Tecklenburg, 2005. High-Resolution Image Rectification and Mosaicing – a Comparison between Panorama Camera and Digital Camera. *Proceedings of the ISPRS working group V/5 'Panoramic Photogrammetry Workshop'*, Berlin.

Mason, S., 1995. Conceptual Model Of The Convergent Multistation Network Configuration Task. *The Photogrammetric Record*, Volume 15, Issue 86, pp. 277-299.

Mikhail, Edward M. and M. Ackerman, 1976. *Observations and Least Squares.* Lanham, New York, London: University Press of America. 497 p.

Mikhail, Edward M., Bethel James S., and J. Chris McGlone, 2001. *Introduction to Modern Photogrammetry.* New York, Chichester, Weinheim, Brisbane, Singapore, Toronto: John Wiley & Sons, Inc. 479 p.

Nebiker, S., and T. Wüst, 2006. 3D GIS Concepts and Technologies Supporting the Integrated Management of Large and Complex Cultural Heritage Sites. In: *Recording, Modeling and Visualization of Cultural Heritage.* Eds: E. Baltsavias, A. Gruen, L. Van Gool, and M. Pateraki. London: Taylor & Francis Group. Pp. 263-273

Nistér, D., 2004. Automatic Passive Recovery of 3D from Images and Video. *Proceedings of the 2nd International Symposium on 3D Data Processing, Visualization, and Transmission* (3DPVT'04), Thessaloniki, pp. 438-445.

Nuikka, M., 2002. *Panoraamakuvien stereomittaus.* Master's Thesis, Department of Surveying, Helsinki University of Technology. 68 p.

Patias, P., 2006. Cultural Heritage Documentation. International Summer School: Digital Recording and 3D Modeling, Crete, Greece. http://www.photogrammetry.ethz.ch/summerschool/pdf/15_2_Patias_CHD.pdf   (7 March 2007)

Pateraki, M., E. Baltsavias, and P. Patias, 2002. Image Combination into Large Virtual Images for Fast 3D Modelling of Archaeological Sites. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Volume 34, Part 5, pp. 440-445.

PhotoModeler Pro, 2004. PhotoModeler Pro 5, User Manual, 30th Edition. Eos Systems Inc.

Pollefeys M., R. Koch, M. Vergauwen, and L. Van Gool, 2000. Automated Reconstruction of 3D Scenes from Sequences of Images. *ISPRS Journal of Photogrammetry and Remote Sensing*, Volume 55, Issue 4, pp. 251-267.

Pollefeys, M., L. Van Gool, M. Vergauwen, F. Verbiest, K. Cornelis, J. Tops, and R. Koch, 2004. Visual Modelling with a Hand-held Camera. *International Journal of Computer Vision*, Volume 59, Issue 3, pp. 207-232.

Powlesland, D., H. Clemence, and J. Lyall, 1998. West Heslerton: WEB-CD, The Application of HTML and WEB Tools for Creating a Distibuted Excavation Archive in the form of a WEB-CD. Internet Archaeology, issue 5.
http://intarch.ac.uk/journal/issue5/westhescd_index.html (15 January 2007)
IBM Systems Journal

Pöntinen, P., 1999. On the Creation of Panoramic Images from Image Sequence. *The Photogrammetric Journal of Finland*, Volume 16, Number 2, pp. 43-67.

Pöntinen, P., 2000. *On the Creation of Panoramic Images from Image Sequences*. Licenciate thesis, Department of Surveying at Helsinki University of Technology, Helsinki. 37 p.

Reilly, P., 1989. Data Visualization in Archaeology., Volume 28, Number 4, pp. 569-579.

Reindel, M. and A. Gruen, 2006. The Nasca-Palpa Project: A Cooperative Approach of Archaeology, Archaeometry and Photogrammetry. In: *Recording, Modeling and Visualization of Cultural Heritage*. Eds: E. Baltsavias, A. Gruen, L. Van Gool, and M. Pateraki. London: Taylor & Francis Group. Pp. 21-32.

Remondino, F. and S. F. El-Hakim, 2006. Image-Based 3D Modeling: A Review. *The Photogrammetric Record Journal*, Volume 21, Number 115, pp. 269-291.

Renfrew, C. and P. Bahn, 1996. *Archaeology, Theories, Methods and Practices*, Second Edition. London: Thames and Hudson Ltd. 608 p.

Reulke, R., K. Scheibe und A. Wehr, 2006. Integration of Digital Panoramic Camera and Laser Scanner Data. In: *Recording, Modeling and Visualization of Cultural Heritage*. Eds: E. Baltsavias, A. Gruen, L. Van Gool, and M. Pateraki. London: Taylor & Francis Group. Pp. 157-167.

RoboGEO, 2007. RoboGEO www-page, Pretek Inc.
http://www.robogeo.com/home/ (9 February 2007)

Rönnholm, P., H. Hyyppä, P. Pöntinen, H. Haggrén, and J. Hyyppä, 2003. A Method for Interactive Orientation of Digital Images Using Backprojection of 3D Data. *The Photogrammetric Journal of Finland*, Volume 18, Number 2, pp. 58-69.

Salemi, G., V Achilli, and C. Cervatio, 2005. Data Acquisition for Cultural Heritage Navigation: Integration of Panoramic Imaging, Terrestrial Laser Scanning and Anaglyphs. *International Archives of Photogrammetry, Remote Sensing and Spatial Informations Sciences*, Volume XXXVI-5/W8.

Schenk, T., 1999. *Digital Photogrammetry*, Background, Fundamentals, Automatic Orientation Procedures, Volume 1. Laurelville, Ohio: TerraScience. 428 p.

Schuhr, W., and E. Kanngieser, 2006. The e-volution of Stereoview Technology in CH data. *The 7th International Symposium on Virtual Reality, Archaeology and Cultural Heritage,* VAST (2006), Cyprus, pp. 186-191

SITO, 2007. Sito Home Page. http://www.sito.fi/english/index.php (23 April 2007)

Stolze, F., 1883. Persepolis. *Verhandlungen der Gesellschaft für Erdkunde.* Berlin 10, pp. 251-276

Stricker, D., M. Zoellner, A. Bisler and B. Lutz, 2006. Travelling in Time and Space with Virtual and Augmented Reality. In: *Recording, Modeling and Visualization of Cultural Heritage.* Eds: E. Baltsavias, A. Gruen, L. Van Gool, and M. Pateraki. London: Taylor & Francis Group. Pp. 431-439.

Schwidefsky, K., and F. Ackermann, 1976. *Fotogrammetria – Perusteita, menetelmiä ja sovellutuksia.* Otaniemi: Otakustantamo. 384 p.

Tsiligiris, E., M. Papakosta, C. Ioannidis, A. Georgopoulos, 2003. Close Range Orthoimage Using A Low Cost Digital Camcorder. *Proceedings of the XIXth CIPA International Symposium 2003.* Antalya, Turkey. http://cipa.icomos.org/fileadmin/papers/antalya/88.pdf (15 January 2007)

Tsioukas V., P. Patias, and P.F. Jacobs, 2004. A Novel System for the 3D Reconstruction of Small Archaeological Objects. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences,* Volume 35, Part 5, pp. 815-819.

Tucci, G., F. Algostino, V. Bonora, and F. Chiabrando, 2003. 3-D Modeling and Restoration: from Metric to Thematic Survey. The Case Study of San Frascesco al Prato in Perugia. *Proceedings of the XIXth CIPA International Symposium 2003,* Antalya, Turkey. http://cipa.icomos.org/fileadmin/papers/antalya/142.pdf (15 January 2007)

Ullrich, A., N. Studnicka, J. Riegl, and W. Neubauer, 2003. 3D-Laser-Sensors and their Applications in Archaeology and Modeling of Historic Buildings. *Archäologie und Computer 2002, Workshop 7.* Wien.

van Maren, G., and R. Germs, 1999. Karma VI: A Virtual Reality Interface for the Spatial Database Engine. *Proceedings of the 1999 ESRI International User Conference,* July 26-30. http://gis2.esri.com/library/userconf/proc99/proceed/papers/pap551/p551.htm (18 January 2007)

Verbiest, F., G. Willems, D. Pletickx, and L. Van Gool, 2006. Image-based Rendering of Cultural Artifacts. In: *Recording, Modeling and Visualization of Cultural Heritage.* Eds: E. Baltsavias, A. Gruen, L. Van Gool, and M. Pateraki. London: Taylor & Francis Group. Pp. 397-406.

Vergauwen, M., D. Pletinckx, G. Willems, and L. Van Gool, 2006. Landscape Reconstruction through Image-based Rendering. In: *Recording, Modeling and Visualization of Cultural Heritage.* Eds: E. Baltsavias, A. Gruen, L. Van Gool, and M. Pateraki. London: Taylor & Francis Group. Pp. 327-337.

Vico, L., A. Moro, F. Galezzi, M. Di Ioia, N. Dell'Unto, 2006. Integrated Methodologies for Data Elaboration and Real Time: Villa of Livia (Via Flaminia project). *The 7th International Symposium on Virtual Reality, Archaeology and Cultural Heritage* VAST (2006), Cyprus, pp. 219-224.

Visnovcova, J., L. Zhang, A. Gruen, 2001. Generating a 3D model of a Bayon Tower Using Non-metric Imagery. *Proceedings of the International Workshop Recreating the Past - Visualization and Animation of Cultural Heritage,* Ayutthaya, Thailand, pp. 30-39.

Vote, E. L., 2001. *A New Methodology for Archaeological Analysis: Using Visualization and Interaction to Explore Spatial Links in Excavation Data.* Ph.D. Dissertation, Brown University, Providence, R.I. 134 p. http://www.cs.brown.edu/research/vis/docs/pdf/Vote-2001-NMA.pdf (15 March 2007)

Waldhäusl, P., and C. Ogleby, 1994. 3-by-3- Rules for Simple Photogrammetric Documentation of Architecture. *Close Range Techniques and Machine Vision, Proceedings of the Symposium of Commission V of ISPRS,* Melbourne, Australia.

Webb, Nicholas J., and Brotherhood, John P., 2002. Virtual Reality Cultural Heritage Information Portal. *Proceedings of the 13th International Workshop on Database and Expert Systems Applications* (DEXA'02), pp. 537-540.

Weinhaus, F. M., and V. Devarajan, 1997. Texture Mapping 3D Models of Real-World Scenes. *ACM Computing Surveys,* Volume 29, Number. 4, pp. 325-365.

Weinhaus, F. M., and R, N. Devich, 1999. Photogrammetric Texture Mapping onto Planar Polygons. *Graphical Models and Image Processing,* Volume 61, Number 2, pp. 63-83.

Wells, D. E., N. Beck, D. Delikaraoglou, A. Kleusberg, E. J. Krakiwsky, G. Lachapelle, R. B. Langley, M. Nakiboglu, K. P. Schwarz, J. M. Tranquilla, and P. Vanicek, 1986. Guide to GPS Positioning. Fredericton: Canadian GPS Associates. No page numbering.

Werner, T., and A. Zisserman, 2002. New Techniques for Automated Architectural Reconstruction from Photographs. *Proceedings of the 7th European Conference on Computer Vision,* Part II, Copenhagen, Denmark, pp. 541-555.

Wilson, D.R., 2000. *Air Photo Interpretation for Archaeologists.* Great Britain: Tempus Publishing. 256 p.

Wong, K.W., 1980. Basic Mathematics of Photogrammetry. Pp. 37-101 in: *Manual of Photogrammetry*, Fourth Edition. Ed: C. C. Slama. Falls Church: American Society of Photogrammetry. 1056 p.