Development of an Integrated Information System for Archaeological Heritage Documentation

Submitted to the University of Cape Town in fulfilment of the requirements for the Degree of Doctor of Philosophy in Engineering

by

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DECLARATION

I hereby declare that this is my own work, that the work of others is accurately reported and that this thesis has not been submitted in any form for evaluation to another university.

Ulrike Karin Rivett

"For in the end, we will conserve only what we love. We will love only what we understand. We will understand only what we are taught."

Baba Dioum, Senegal

Abstract

The traditional methods for the documentation of archaeological heritage sites are challenged today by developments in geomatics, information technology and the computer industry. Non-contact spatial measurement methods, as well as new spatial information systems technologies and computer visualisation tools have introduced a new age for conservation and site research.

This thesis uses the instance of the documentation of the 3.6 million-year-old hominid footprint trackway in Laetoli, Tanzania, to address the need for an adequate scientific method to acquire, manage and visualise spatial data for the re-creation of archaeological heritage sites in a three-dimensional virtual world.

The Laetoli site presents the first physical evidence of human bipedalism. Its consequent significance to human evolutionary science justifies the need for highly detailed and accurate documentation of its characteristics. The thesis explores digital photogrammetric techniques as data acquisition tools for this kind of close range archaeological environment. Specifically, it examines issues such as non-contact measurements, cost-effectiveness, and functionality in harsh conditions.

The data collected at Laetoli had to be organised, managed and presented to allow future research on the footprints and to allow the general public to "visit" the site. This thesis shows how a spatial information system is used to manage spatial and meta data, while an integrated visualisation tool offers a virtual 3D reconstruction of the heritage site.

Acknowledgements

This thesis is based on the Laetoli conservation project. In order to produce a permanent record of the hominid trackway site at Laetoli, Tanzania, the Getty Conservation Institute instructed in 1995 the Digital Photogrammetric Research Group from the Department of Geomatics at the University of Cape Town to survey the site photogrammetrically.

The work was carried out in three stages: project design, field work and post processing of the data. After the design of the project by Prof Heinz Rüther, the project leader, the first photogrammetric field campaign took place in Laetoli in August 1995. Prof Rüther and Julian Smit, a former PhD student of the Department, joined the Getty Team in Laetoli and acquired the imagery of the southern section of the trackway. After returning from the field trip, the photogrammetric post processing began. Various postgraduate students helped to process the data by providing software and assisting with data input. In this context Henty Waker, Malcolm Dingle, Siddique Motala and the technical officer of the Department Sue Binedell have to be thanked. Julian Smit managed the data processing stages and ensured a successful hand-over of the ortho-images in February 1996.

I joined the team for the second field trip to survey the northern section of the trackway in August 1996. After the processing of the data and the subsequent hand-over in February 1997, the idea of an information system and a visualisation tool developed. In light of the vast amount of data (the photogrammetric survey alone resulted in nearly 15000 files of data) it became clear that a system for the management, retrieval and visualisation of the data was needed. Prof Heinz Rüther encouraged me to investigate the possibilities of an archaeological information system and to intensify my research in this area, which resulted in this PhD thesis.

I would like to extend my sincere gratitude to Prof. Heinz Rüther for his support, advice and encouragement over the last five years. His family offered me my first home in South Africa and I was very privileged to take part in his project.

I was very fortunate to be able to work with a great team of postgraduate students who joined the Department in January 1998:

Terry Richards coded the Laetoli database that fulfilled all the expectations and who exhibited immense patience in spite of a never-ending list of changes. She was able to upgrade her Masters to a PhD in the field of information management. All the best for your PhD-challenge and thanks for a great time!

Simon Taylor created the Laetoli Web Page and kept the attitude of the team up by supplying creative ideas and games from the Internet. He graduated with his MSc. (Eng) in June 2000, the title of his thesis was: "3D Visualisation of the Laetoli Footprints on the Internet". Thank you very much for all your input!

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My dear parents, who loved me, supported me, and educated me to do what I believe in and who always believed in me.

The final and deepest gratitude I owe to my husband Ian, who was in this demanding time my best friend, adviser and supporter. You stood by my side through the weekends and evenings of 'phding' and made me succeed. Thank you for all your selfless support, understanding and love.

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A INTRODUCTION

1 The World's Heritage

The world's cultural heritage sites provide important clues to an understanding of the past and present of human society. Recognising this, a number of archaeological and conservation institutions throughout the world have made it their mission to record, analyse and preserve sites that contain evidence of the evolution of mankind.

One such site is the trackway of 3.6 million-year-old footprints in Laetoli, Tanzania, which represents the first evidence of bipedal walk of the ancestors of humankind. The fossilised hominid footprints were found during a palaeontological expedition led by Mary Leakey in 1978 and were described by Johanson (1989) as "the most precious discovery that has ever been made in this science, or ever will be made".

The discovery attracted great scientific and public attention (Leakey 1984). The examination of the prints raised fascinating questions and led to a diversity of opinions on topics ranging from locomotion capabilities to the social behaviour and the phylogenesis of early hominids.

Besides being widely seen as a proof of the existence of hominid bipedalism as early as three and a half million years ago, the Laetoli footprints resolved one of the major issues in the field of palaeoanthropology, as stated by Agnew and Demas (1995): the debate over "the development of the brain in relation to our ancestors' ability to walk upright."(Agnew et al. 1995).

The evolution of the human brain, which differentiates humankind from other creatures, was defined by the ability to make stone tools. This was seen as a key factor in the emergence of early man. Before the discovery of the Laetoli footprints two theories had developed:

- The first theory was that the development of the brain was possible due to the development of upright walking. Since the hands were no longer needed to support walking, they were free to evolve manipulative skills, which lead to tool making and, subsequently, the development of brain. This theory of early bipedalism states that upright walking came before the brain developed.

- The second theory was that the brain developed before bipedalism. As a result of brain development, the decision to walk upright became possible and subsequently enabled early man to make tools.

Although functional analysis of hominid bones from Africa pointed to the first theory of early bipedalism no definite answer was possible prior to the discovery of the trackway.

As Agnew (1995) states, the 3.6 million-year-old footprints settled this issue. Since the earliest stone tools known are 2.6 million years old, the theory was confirmed: bipedialsm evolved well before tool making. This provided evidence that upright walking led the way for the evolution of the human brain (Agnew et al 1995).

The importance and fascination of the trackway uncovered in Laetoli required a new way of allowing as many people as possible to explore the evidence for themselves. This resulted in researching a new method of documenting and disseminating information on the heritage of humankind.

The methodology developed in this dissertation offers a new approach to the conventional documentation, information management and data visualisation of archaeological sites resulting in the enhancement of research potential.

2 The Laetoli Project

The geological formation known as the Laetoli beds are situated on the Eyasi Plateau and the Serengeti Plain in Tanzania and cover an area of $1500km^2$.

Figure 1 Part of Tanzania with the Olduvai Conservation Area

Laetoli is the fossil richest place within the Laetoli beds and lies at an elevation of 1700 to 1800m, near the drainage divide between Lake Eyasi to the South and Olduvai Gorge to the North and occupies less than $70km^2$. The footprints were found in this region preserved in a layer of volcanic tuff.

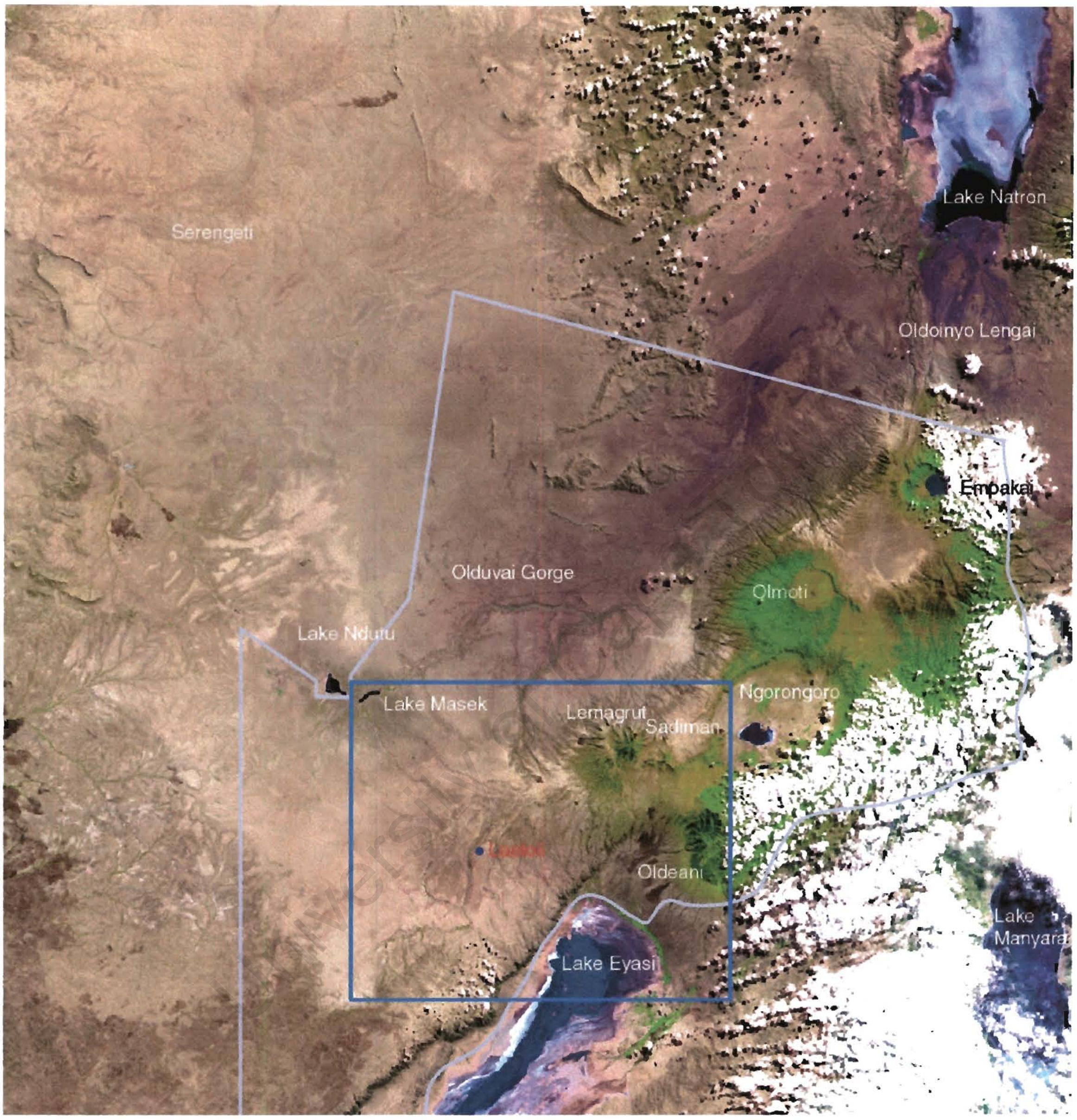


Figure 2 Olduvai Gorge and Laetoli beds (blue area), © Getty Conservation Institute, processed by Rand Eppich from Landsat raw data

Excavation of the hominid trackway site in 1978 revealed two parallel tracks of hominid footprints - one with small imprints and one with considerably larger ones - generally attributed to Australopithecus Afarensis. Initial interpretations suggested that the smaller imprints originated from a single small individual, while opinions varied on the larger imprint. A widely held scientific opinion is that the earliest ancestors of humankind were - like orang-utans and gorillas - sexually dimorphic, with males much larger than females. Thus the smaller trackway may have been made by a female and the larger trackway by one, or possibly two males. The imprint of a second big toe in several of the larger imprints suggests that a second individual may have walked in the footsteps of the first (Leakey 1984).

After the first excavation of the hardened volcanic ash (tuff) surface the fragile site had to be protected. To accomplish this, scientists chose to rebury the entire track, covering it with layers of sand and lava boulders. However, a site inspection in 1985 showed that these efforts to protect the footprints had partly failed, because Acacia trees were growing over the buried prints.

As a result of damage caused by roots penetrating into the tuff layer, the track had lost some of its scientific value and as stated by Johanson (1989) had suffered more deterioration in the 10 years since its discovery than it had in the 3.6 million years before (Johanson, 1989).

The Getty Conservation Institute (GCI), in collaboration with the Government of Tanzania, subsequently began a joint project to conserve the Laetoli hominid trackway. Fundamental to this project was the understanding that the trackway would be reburied after the conservation, since placing a protective shelter over the trackway or removing the entire trackway to a museum were not practical alternatives for its protection. Owing to the cultural and scientific importance of Laetoli in the history of human evolution, and considering the fact that only a few researchers had seen the exposed footprints, the documentation of the site demanded an exceptionally high level of detail and accuracy. Although the loss of information could not be undone by conservation, further deterioration could be prevented by eliminating the causes of damage and what scientific value remained in the trackway could be enhanced through appropriate methods of documentation (Demas 1993).

The conventional methods of documenting and recording archaeological sites were challenged by requirements and constraints specific to the Laetoli site:

1. The site was excavated over a very short period of time to treat and conserve the footprints and was then reburied. The survey and documentation had to be done during the time of exposure, which was limited to 50 days.

2. Due to the reburial of the trackway there was only a once-off possibility for data acquisition.

3. The entire trackway had to be mapped.

4. The fragile surface of the trackway was declared a 'no-go' zone and contact with heavy weights was prohibited. All necessary instruments of measurement had to stay outside the site border.

5. The site is exposed to natural elements. The measurement equipment had to be robust and reliable in order to be used in this environment.

6. The site is located in the Serengeti and all equipment, including backup for some instruments, had to be transported to this remote location.

7. The spatial data acquired had to be presented in a form that was easily accessible to and understood by a broad range of users, including conservation professionals, archaeologists, palaeo-anthropologists, geomatic experts, professionals of other disciplines and the general public.

The project, including re-excavation, conservation, photographic and photogrammetric recording, scientific restudy, and reburial, was completed in four phases, from 1993 to 1997. The Digital Photogrammetric Research Group of the Department of Geomatics at the University of Cape Town (UCT) joined the two major field campaigns in 1995 and 1996 and produced complete photogrammetric coverage of the hominid trackway. The first photogrammetric field campaign in 1995 was planned and executed by Prof. Heinz Rüther as a project leader and Dr Julian Smit. The author joined the second campaign and was involved in the photogrammetric processing of both campaigns. Various postgraduate members of the Department and Dr Manos Baltsavias from the ETH Zürich supplied non-commercial photogrammetric software, which was used for the processing of the acquired data and to produce ortho-images.

3 Thesis Overview

The Laetoli Conservation Project brought to light the need for an adequate scientific method to acquire data in a sensitive archaeological environment. A number of methods are established to perform close range measurements, such as tacheometric surveys, photogrammetry or laser scanning. These technologies had to be investigated and translated into a feasible methodology, which had to be non-intrusive and cost-effective, allowing a fast and efficient data acquisition. Besides that it also had to be suitable for a remote site, which is exposed to natural elements.

To create an environment, which allows the user to 'see' the site and its objects in a real-world scenario and to use the acquired data to its fullest extent it had to be managed and organised in a sensitive manner and presented visually in a meaningful way.

In order to address the needs of a wide audience - from scientists to interested laypersons - the visualisation of the collected three-dimensional information had to

- satisfy the requirements for further research, such as measurement tools, possibilities of creating 'what if' scenarios, completeness and detail of the displayed material

- allow for the extraction of information requested by individuals; and

- give the general public the opportunity to explore the site in a virtual environment.

3.1 Thesis Objectives

This thesis can be divided into three sections, with the following objectives:

Objective 1: Description of the method that was used to acquire data using non-intrusive methods in an archaeological environment (Chapter 5).

Objective 2: The development of a pragmatic and dynamic model for the management of data associated with the conservation and documentation of archaeological sites (Chapter 6).

Objective 3: Data representation and visualisation of 3D data (Chapter 7) with the possibility of interacting on-screen and exploring the data.

To address these three objectives the fields of digital photogrammetry, information system technology and scientific visualisation were combined. A method was designed that offers the re-creation of an archaeological site in a three-dimensional virtual reality environment, which is spatially correct and communicates information about the site or project interactively, between disciplines and world-wide.

3.2 Thesis Outline

This thesis is divided into a further 9 chapters, which are organised into three sections following on the introduction of ***Section A***:

Chapter 4 provides a brief review of some literature covering areas relevant to this research.

Section B (chapter 5 to 7) presents a novel method for creating an integrated spatial information system for archaeological heritage documentation.

Chapter 5 describes the methodology designed to acquire data photogrammetrically in the archaeological environment, in view of using the data for the creation of an information system.

Chapter 6 introduces Information Systems and deals with the design of specialised databases, which were examined and developed for implementing into the integrated spatial information system (ISIS).

Chapter 7 provides a brief overview of scientific visualisation and discusses the possibilities of combining visualisation tools and information systems.

Section C reports on the Laetoli project and shows an application of the developed methodology. This section is subdivided into chapters 8, 9 and 10.

Chapter 8 describes the photogrammetric data acquisition and the data processing of the Laetoli site.

Chapter 9 provides an overview of the development of the integrated spatial information system Laetoli. The strategic planning stages and the database development process are explained.

Chapter 10 describes the design of the Laetoli visualisation tool from the task definition stage to the choice of the right approach. The developed Web Page and the integrated visualisation tool are presented.

Chapter 11 concludes Section C by summarising the technique used and offering recommendations regarding the development of specialised information systems.

Section D draws some conclusions regarding the suitability of the methodology developed, the advantages and disadvantages, and makes some recommendations for future development of integrated information systems.

The *appendices* describe additional information relevant to this thesis. The first section gives an overview of the fundamentals of photogrammetry. The second section presents some tables, questionnaires and images pertaining to the development of an integrated spatial information system. The third section contains image plates presenting the results of the Web Page and the visualisation tool.

4 Literature Review and Project Rationale

This thesis attempts to answer the following research question:

How can information technology support archaeologists and conservators by providing a more effective method of site documentation?

Before commencing with any research project it is important to establish its relevance. This chapter gives the reader a short review of the research done within this field and justifies the relevance of this dissertation.

Palumbo (1999) reminded the archaeological community, at the World Heritage Conference 1999 in Cape Town, of the code of ethics of the Society for American Archaeology (SAA). This code refers to archaeological heritage sites as a "public trust" and emphasises that archaeological records should benefit all people. Archaeologists are scientists who have made it their profession to protect, preserve and record heritage sites and their objects. The ethical codes of the SAA name "Stewardship" as the first principle of archaeological research, implying that archaeologists should serve as caretakers and advocates that: "As they investigate and interpret the record, archaeologists should also promote its long-term conservation. Archaeologists should use their specialised knowledge to promote public understanding and support for the long-term preservation of the archaeological record." (Lynott et al.1995, as quoted in Palumbo 1999).

The Laetoli project serves as a good example to test a new approach to the long-term conservation of a site and the distribution of the acquired information to the general public and interested scientists.

Since the discovery of the hominid trackway challenged previous theories regarding the evolution of man, various discussions between leading scientists ensued, which made the research and the interpretation of the evidence particularly important.

One point of discussion was the origin of the footprints. Scientists disagreed about the species of hominid that left the prints. Most scientists believed that they were made by hominids of the species Australopithecus Afarensis as described by White (White et al. 1987). Others, like Leakey (1984), resisted assigning them to any species. But nobody seemed to challenge the idea that they were made by direct human ancestors, as asserted in the first photogrammetric analysis of Day and Wickens in 1980. This analysis proved that the hominids transmitted their body weight and exerted forces of propulsion to the ground in a similar way to that of modern man (White et al. 1987).

As Agnew (1998) explains, other disputes concerned the number of hominids that made the trails (chapter 2) and questions arose about where the hominids were coming from and where they were going to. Scientists also wondered why they had stopped to look back, as is evident from some prints at the northern end of the site. It was discussed whether the hominids were part of a family and how they communicated. All these questions required answers (Agnew et al. 1998).

Much of the controversy over the footprints was based on the fact that only a selected number of scientists had the opportunity to study the prints in situ in Laetoli. Leakey's team buried the prints after each field season and although casts were made of the best preserved sections and the fieldwork was documented, not everybody had access to examine the prints.

This highlighted the need for a method of information dissemination that accurately communicates data and can be used by scientists outside the field project for the purposes of research.

One of the goals of information technology is to manage and distribute information, so it seems logical to employ these techniques - especially since they offer effective and efficient methods of data processing.

The possible uses of computer technology and its related fields in an archaeological environment have been discussed intensively by archaeologists over the last decade (Reilly et al. 1992, Gidlow 1999, Lock 1995, Potel 1997). In the 1970s regular meetings of archaeological computer enthusiasts developed into the "Computer Applications in Archaeology Conference", which was later renamed the " Computer Applications and Quantitative Methods in Archaeology". This small group became a large international community. The question these meetings, symposia and workshops tried to answer was "Where and how does information technology fit into archaeology"?

In the past computers have been used in archaeology to store, maintain and share data, but not to enhance analytical process scenarios. More and more archaeologists are recognising this. For example the Institute of Field Archaeologists (IFA) of the United Kingdom states that it "considers it to be important that archaeologists are properly trained in the use of computers" and it is therefore "encouraging the provision of appropriate courses and the development of computing resources"(Reilly et al 1992). In the USA archaeologists are generally trained in quantitative methods and the use of statistical and simulation approaches. Internationally there seems to be a growing trend amongst archaeological academics to investigate the use of computer technology for research purposes.

Over the last decade archaeologists have become increasingly sophisticated in their use of information technology. Conferences in the fields of archaeology, photogrammetry, computer vision and information management show various methods for applying techniques of computer and information technology in the field.

Herbig introduced an Architectural Photogrammetry Information System APIS at the CIPA International Symposium in 1997, and showed the usefulness of such a system using the example of the restoration of the Hofburg in Vienna. The aim was to create an opportunity for everyone to use an amateur camera for stereo block documentation (Herbig et al 1997).

Camara (1997) developed an information system design for heritage conservation, which serves as a support for the planning and management of site conservation. He suggests close-range photogrammetric techniques for data acquisition and employs CAD software for the re-construction of the conservation site. He proposes that data management should be done using a relational database approach.

McCready, in turn, investigated the use of geographic information systems and digital field collection techniques as an aid to archaeological research (McCready 1997).

A number of specialists in the field of geomatics have tried to find the right approach for efficient digital data acquisition, providing non–contact measurements for archaeological sites and artefacts.

There are a number of techniques that allow for the digital acquisition of points in 3D space with the aim of establishing point fields describing the surface of an object. Miyatsuka (1998), for example, uses a cavity monitoring system that measures up to 20 points per second using a laser range finder. The system was very successfully employed for the reconstruction of the Han As'sad Bacha in Damascus and also served as a data acquisition tool for an archaeological 3D GIS for a virtual Museum in Damascus. The drawbacks of the system are that the machinery itself is very sensitive and that spatial shadow areas will not be detected so that a number of setups are necessary to record all detail on complex sites.

Abe (1998) introduced the magnetic resonance imaging (MRI) technology that uses magnetic resonance to measure the fragments of relics and restore them virtually. Using a data glove, magnetic sensors and a head mount, Abe shows the restoration of relics in a virtual environment. One of the advantages of this technology is that both sides of the fragment can be measured three-dimensionally at the same time with high accuracy. The disadvantage of the system is that the MRI signal only responds to organic substances, inorganic objects have to be treated with agaragar jelly, which can be difficult and the measurement of the object may not be successful.

Agnard (1998) introduced another data acquisition tool, the digital photo-theodolite. It combines a Leica TC1600 total station with a Kodak DC50. The combination of the expensive total station and the cheap digital camera results in an acquisition system that allows for a conventional data acquisition as well as providing an image. The overall accuracy is limited due to the resolution of the camera.

Laser Scanners are being employed more frequently for image acquisition, sometimes in combination with digital cameras (Bacugalupo 1998). Chen (1998) describes the techniques of TLS (three-line sensors), which use a triplet of linear CCD cameras to record the object of interest.

Data visualisation is another area that holds promise for the future of archaeology. The documentation of sites is generally done using maps and photographs. But the virtual reconstruction of sites using computer visualisation creates a "real world scenario", allowing scientists who have not actually seen the object to visualise it accurately. This kind of generated visual information can also be shared more easily using facilities such as the Internet.

Archaeologists are often faced with situations where a site or artefact is partially or totally ruined. The tools of computer visualisation allow them to reconstruct and "fix" the virtual object (Palamidese et al 1993, Taylor 2000, Rozendaal 2000, Hull 2000).

3D computer visualisation can support the identification of an object by offering multiple perspectives of the same data.

Figure 3 shows a conventional contour map. The user looks at the map and creates a conceptual model of the surface represented. In a best-case scenario the user should be able to create an imaginary model of Figure 4, which shows a different perspective of the same surface.

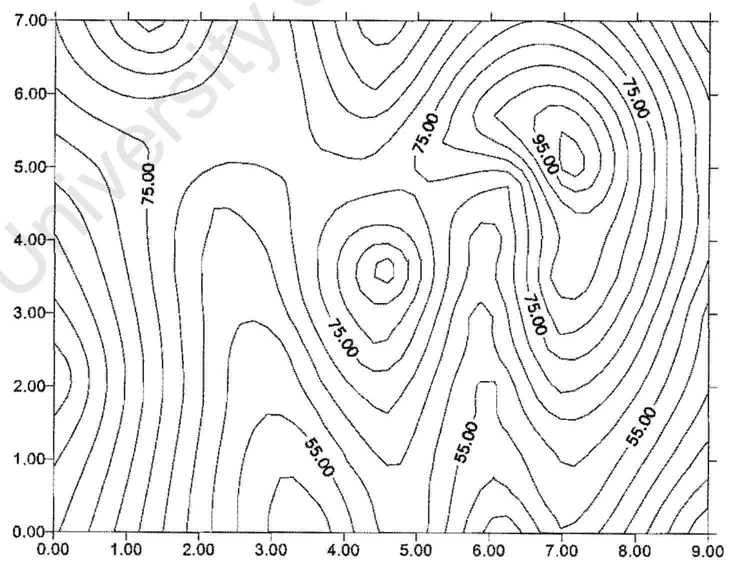


Figure 3 Contour Map

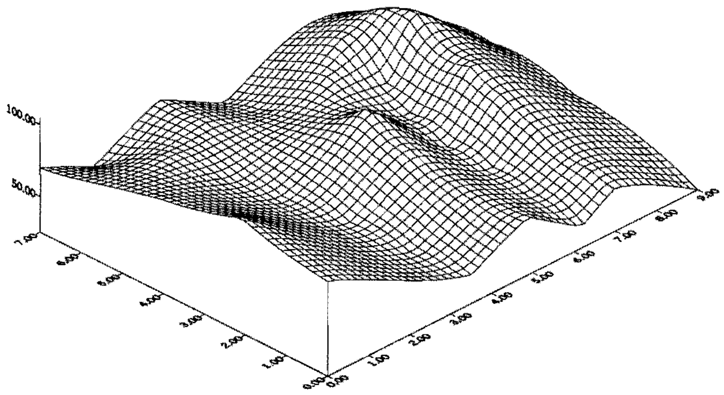


Figure 4 Surface

Computer visualisation on the other hand provides technology and tools that can display data in models such as Figure 4, which can immediately be identified without requiring the user to build a conceptual model.

As Alexander von Humboldt puts it:
"Panoramas are more productive of effect than scenic decorations since the spectator, inclosed as it were, within a magical circle, and wholly removed from all the disturbing influences of reality, may more easily fancy that he is actually surrounded by a foreign scene." (Humboldt, 1813)

Various authors show very convincing examples of the use of visualisation in archaeology (Taylor 2000, Rozendaal 2000, Hull 2000).

Ogleby introduces a method of building models of ancient cities using the techniques of virtual reality (Ogleby 1997); Potel shows how the reconstruction of Michelangelo's Florentine Pieta is achieved using computerised visualisation (Potel 1997).

Gidlow argues that despite the evidence of the usefulness of computer technology in archaeology, most archaeological publications "seem to be reluctant to see computer generated archaeologies as an appropriate context for reflexive interpretations". The apprehension is based on a fear that computers will be used with an agenda, thus risking the production of "politically correct" archaeologies as prescribed by governmental or other authorities (Gidlow 1999). It is argued that archaeologists are not in control of the individual processing steps, but are rather presented with a result, which has been "produced" in a "black box" fashion by the computer. Concern has also been expressed about the use of information systems such as geographical information systems (GIS) in archaeology. If GIS is only a more dynamic way of representing, storing and handling spatial information, it becomes subservient to any theoretical approach employed by archaeologists. As Gidlow summarises, all concerns are based on the question of the reliability of digital testimony. Assuming that computers would allow the archaeologist to create scenarios and test theoretical approaches, how reliable would these outputs be, and more importantly, how seriously would they be taken by the community of archaeologists? "If computers are purely modest 'eyes' for archaeological analyses, there is no room for reflexive or multiple interpretations in this medium"(Gidlow 1999).

In responding to these concerns lies the challenge of creating an information management system that is designed and developed by archaeologists and offers more than simply data management. If the system is well designed and flexible enough for the needs of the archaeological scientist, it should be possible to break the perceived apprehension and address the above-mentioned concerns.

Having accepted the relevance of computer technology in the field of archaeology and assuming that information technology offers the solution, this thesis attempts to answer the question how information technology can be used and proposes a methodology by demonstrating the development of an information system for archaeologists.

It is not within the scope of this thesis to discuss the physical archaeological conservation of heritage sites, that must be left to archaeologists and conservationists, but a method is proposed for "virtual" conservation.

The author draws on some of the findings and experiences reported in the literature, discussed above, in order to develop an integrated spatial information system that addresses the previously mentioned concerns of data distribution, visualisation and flexibility.

B DESIGN OF A METHOD FOR THE DOCUMENTATION OF ARCHEAOLOGICAL HERITAGE SITES

The purpose of this section is to present a methodology for the documentation of archaeological heritage sites.

Chapter 5 introduces an approach for the collection of spatial data by means of close range photogrammetry. The spatial data acquisition is a very important part of the documentation of a site, since the data obtained forms the base for a visual re-creation of the site. A methodology for photogrammetric project planning is developed and methods are described for high precision surveys, photogrammetric data acquisition and processing.

Chapter 6 shows the management and organisation of the data so that all information related to a site can be restored. The creation of an Integrated Spatial Information System (ISIS), which combines various spatial and non-spatial data, is described.

Chapter 7 introduces the representation of 3D data in an information system context and a methodology for the creation of a meaningful display of archaeological data is established.

5 Close Range Photogrammetric Data Acquisition in an Archaeological Environment

5.1 Introduction

During the archaeological fieldwork a detailed documentation and recording of the site and its objects is generally carried out. This is very important, since future research often relies largely on the recorded data. The field documentation usually entails a spatial recording of the site and the objects of interest, a compilation of descriptive and textual information, and a collection of supportive material such as drawings and photographs.

Archaeological sites are by and large sensitive environments (e.g. fragile surfaces) and contain delicate objects. In general the spatial recording of the site involves the survey of each site object and the site itself relative to an established co-ordinate system. Conventional survey techniques, such as tacheometric surveys, can be employed, but have a number of limitations. The density of the points surveyed may not completely cover the site. Archaeological sites are often difficult to reach (e.g. caves) and it is thus not always easy to set up the necessary equipment.

The alternatives to tacheometric surveying are either the application of photogrammetric methods or the latest technology of laser scanning. Both techniques allow non-contact measurement without jeopardising accuracy. Laser scanning is becoming more and more popular, since it is both fast and accurate. However, one disadvantage is that, to date, the laser itself is a sensitive and expensive piece of equipment and may not be able to operate in the harsh conditions of an archaeological site environment, such as the Laetoli site (page 6).

The methods of digital photogrammetry avoid unnecessary contact with the object. A bar or a scaffold may serve as a platform and the camera can be "flown" over or along the site at the desired height. Theodolites are, in this context, only used to establish a control network and do not need to be physically close to the object itself. Images can be acquired remotely by using a shutter release cable. Digital cameras allow easy and fast image acquisition and can be employed in the field environment under most circumstances.

The greatest advantage of digital photogrammetry is the amount of detail acquired. No other method offers the acquisition of a similar point density with relatively little effort. In the Laetoli project up to 18 000 points were captured for an individual footprint (ca. 23cm x 10cm) by taking six digital pictures. It is arguably impossible to capture similar detail with a comparable amount of effort by using conventional methods.

Through digital image acquisition it is possible to make decisions about image quality in the field and to transfer the images on-line to a computer for processing. This guarantees the efficient production of high quality data. The completeness of the data coverage can be ensured by creating a high point density through mapping of all image elements. Since most of the data processing is automated, results are produced relatively quickly, without subjective judgement and with a high accuracy.

One of the major advantages of photogrammetry is that photographic images create realistic impressions of an object. Technologies such as scientific visualisation can be used to create 3D models and virtual reality displays, which are not only a visual representation of the acquired data, but allow a scientific re-design of a realistic site and its objects.

The use of digital photogrammetry results in a number of products:

- Point clouds

  Point clouds represent the surface or object through points with three-dimensional co-ordinates. They are an unordered set of values and serve as base data for surface models, contour maps and visualisations.

- Surface models

  A three-dimensional surface represents an object and defines it in object space. Digital terrain or surface models are an ordered set of values, which describe the spatial distribution of topographic and object features by connecting and grouping point clouds to represent the topology of the object.

- Contour maps

Contour maps provide support for the understanding of the three dimensionality of the object or surface. Height changes in the surface can be identified by lines of equal elevation. Generally one requires some training to understand 2D contour maps and to be able to perceive the 3D shape of the object. With the technology of computer visualisation, overlays of contour maps onto ortho-images or 3D surfaces can be achieved. This simplifies the identification of height changes and the object is easily visually reconstructed.

- Ortho-images or Ortho-maps

Maps are a very popular way of recording spatial data and information related to an excavation. Digital image rectification is the photogrammetric process in which a 'map-image', the orthogonal projection of the original image, is produced. This image can be used as a map and is very often overlaid with combinations of different information and serves as base data for information systems.

- 3D visualisation

The term 3D visualisation refers to visualisation of the object on a computer screen using the acquired spatial data. Computer visualisation includes solid or wire frame representations, 3D walk- or fly-throughs, overlays of surface models with ortho-images or contour maps, shading, graduated colouring of different height levels, etc. In the archaeological context it is employed, for example, to reconstruct artefacts on screen. A broken vase can "virtually" be glued together by measuring dimensions and moving the individual pieces to where they belong (Abe et al. 1998). Scientific visualisation is a very popular way of representing spatial data and helps to extract information easily and quickly.

Figure 5 presents an overview of Section B and its objectives. Chapter 5 introduces the Objective 1, which presents a method to document an archaeological site spatially, using digital photogrammetry. The various stages from project planning to the photogrammetric data processing are shown in detail and explained in the sub-chapters. Objective 2 is dealt with in chapter 6, which describes a methodology to manage the acquired data in a spatial information system. The last objective, to create a visual display of the site and its artefacts, is introduced in chapter 7.

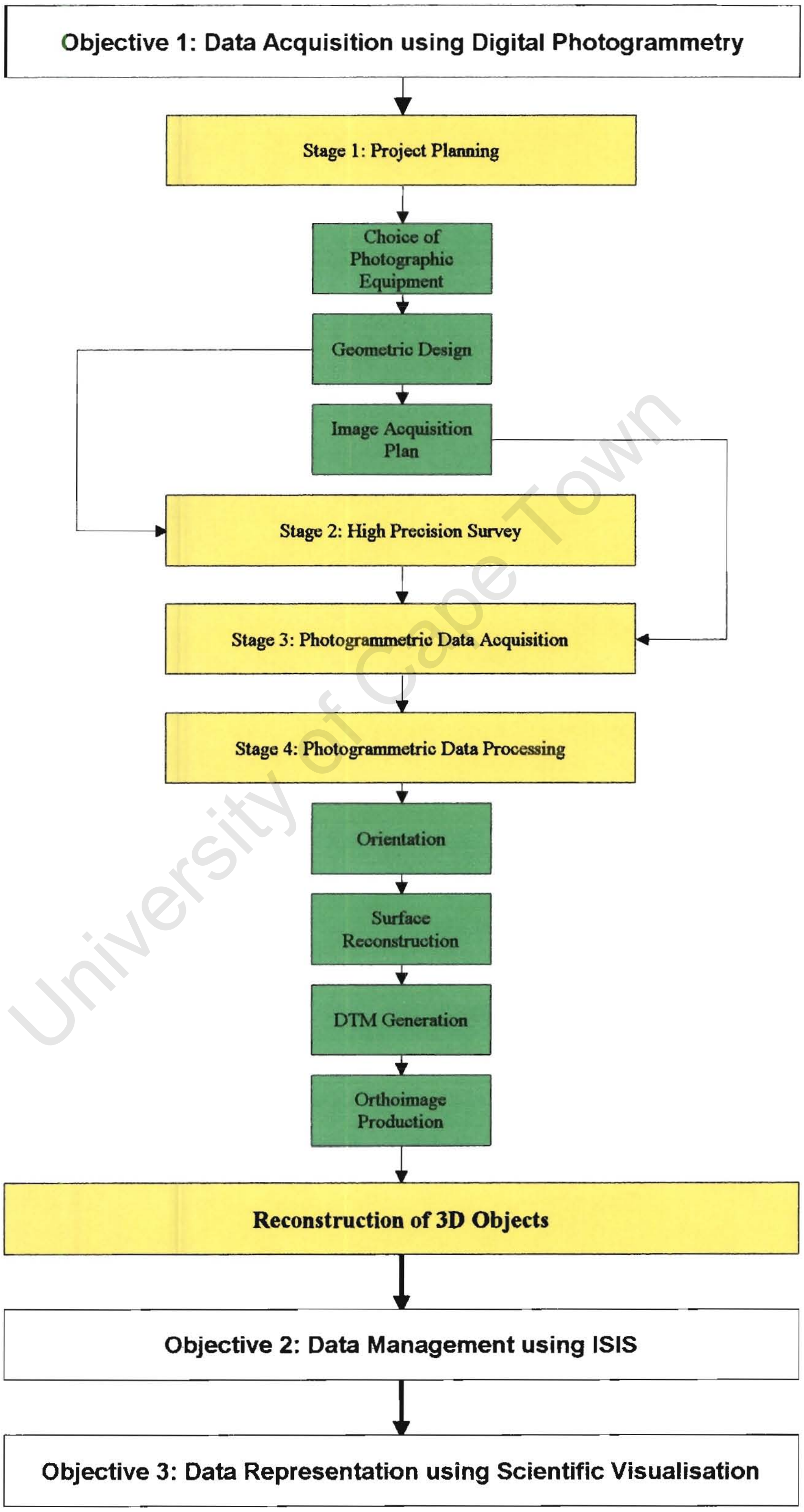


Figure 5 Chapter Overview

5.2 Stage 1: Photogrammetric Project Planning

Successful data acquisition in a photogrammetric project depends, like in any other project, on a well-defined project plan that presents the goal of the project.

The project plan focuses on the purpose that the photogrammetrically acquired data will serve. A detailed definition of this purpose is crucial, since it dictates the major project design parameters. The eventual use to which the images are to be put will influence the requirements for the data quality and equipment, as well as the project's cost.

After the purpose has been established, the project plan is being designed. The project plan can be viewed as being a strategic plan, which translates the aim of the data acquisition into individual project steps, considering all constraints and requirements.

The most important questions to ask during the project plan design stage are:

- What are the quality requirements of the output data, e.g. accuracy, level of detail?
- What are the equipment requirements, considering the purpose and the level of accuracy of the data?
- What are the financial constraints?
- What logistics have to be considered?

Once these questions have been answered, decisions will be made about:

- The data quality – what level of accuracy and detail is possible considering constraints such as finances, time and the necessary equipment?
- The equipment to be used – which equipment will provide the highest possible level of data quality, considering constraints such as finances and the site environment?
- The design of a control network – what is the most economical network layout?

- The design of an image acquisition plan – how many images will have to be taken, how much time will be needed, what backup images will have to be made?

- The financial outlay – what are the expected costs and do the available finances allow for the acquisition of data at the required level of accuracy within the required time-span?

- Logistics – how will the equipment be transported, how much extra time is available, is there electricity on site?

For archaeological documentation, the goal may be to produce a map of a site, or to establish an advanced virtual representation of the site, implemented in a spatial information system of the project. A basic product, such as a map, generally requires only the acquisition of the minimum number of images. For an advanced product, such as a virtual reality model combined with a spatial information system, data acquisition has to be approached differently. In this case, the images will be used to form the base data of an information system and, as such, they merit a high level of detail. The object is re-constructed using not only the data extracted from the images, but the images themselves. A number of products, such as surface models, ortho-images and virtual models may need to be created. Data completeness and quality of the images therefore take on a very high priority. Objects such as control frames and control points (Figure 48) in the images disturb the visual impression of the re-constructed model and have to be avoided. This might mean the acquisition of additional images, which has an impact on the time, effort and financial resources spent on the project.

The difficulty lies in establishing what products are required to build a 3D model before the actual data acquisition. In this context it is important to establish first of all for whom data is captured. Will it be research material for specialists? Will it merely serve as a record of the fieldwork for future reference? Or will it be displayed in a museum? Is the community that will use the data a specialised group, or will it address a wider audience (chapter 6.3 and chapter 6.3.2.1)? A purely documentational data acquisition aimed at the general public may not need the same level of detail that a scientist would expect for his[1] research.

Once the purpose of the data acquisition is established, the required quality of the data can be determined.

The quality of photogrammetric data is comprised of a number of interrelated parameters such as accuracy and completeness. To optimise the data acquisition, particular attention has to be paid to these quality parameters.

Completeness is critical for the quality of the final product. The issue of representativity has to be addressed, e.g. how many points are needed to meaningfully represent the object of interest. Information loss due to vision and light shadows on the images would result in "holes" in the ortho-imagery. Thus, the lighting situation, the time of the day, the number of images, the image geometry and the sequence of the image acquisition have to be considered in the project plan.

Along with the definition of the purpose and the quality of the data, the equipment requirements need to be ascertained (Chapter 5.2.1).

Financial constraints have to be established before the detailed planning stages can proceed. The overall costs of a photogrammetric project include a number of different aspects. The main cost factors are generally the purchase of new hard- and software and manpower. High quality products require an extensive time frame, which can also have a great impact on the financial resources. A compromise has often to be found between what is possible and what is reasonable financially.

The flowchart (Figure 6) below shows the relationship between the three major design parameters of quality, equipment and finance and tries to clarify the decision making process. The project requirements can be translated into the data quality required, the equipment required and the financial framework. Out of these three a principal criterion has to be chosen. If, for the example, the quality of the data has highest priority, it would

[1] 'He' and 'his' are used throughout the thesis as neutral terms, representing he/she, his/her.

be made the principal criterion and data quality (column left) will be applied. The first step is to establish whether the available equipment will fulfil the quality requirements. If this is the case, then the established project requirements can be accepted and the detailed planning can begin. If not, it has to be established whether to compromise the data quality or upgrade the equipment, which in turn influences the finances. There is a direct relationship between the equipment and the quality of the data, which can be compromised by decreasing either the level of accuracy or the level of detail.

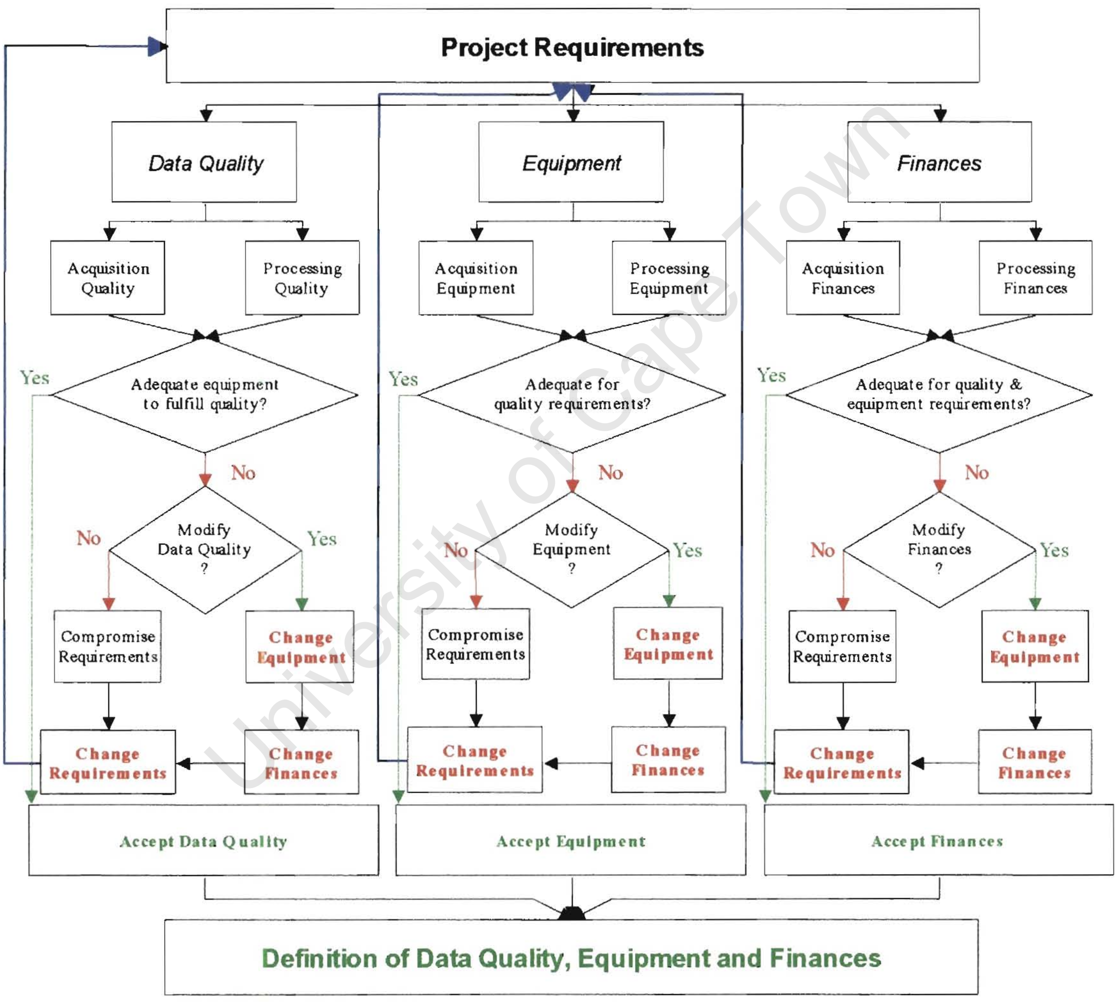


Figure 6 Flowchart for the Definition of the Project Requirements

Assuming that the data acquired will be incorporated in an integrated information system, providing virtual reality displays and addressing a scientific audience, the purpose of the photogrammetric data acquisition would be defined as the supply of base data for a digital three-dimensional representation of a site allowing accurate on-screen measurements of object co-ordinates. Thus the photogrammetric products required would be a digital terrain model and ortho-images with a predefined contour line interval of 1mm and a certain standard of quality (e.g. accuracies better than 0.5 mm in all three co-ordinate axes). Since the target audience has a high interest in data accuracy, the data quality element would be chosen to have the highest priority. The overall data quality is determined by the quality achieved during the acquisition and post-processing, which is influenced by the performance of the equipment used. Therefore it is necessary to test whether the equipment is adequate to fulfil the requirement of producing accuracies better than 0.5mm in all three co-ordinate axes. If so, then the established accuracies, equipment and financial frameworks can be accepted. If the equipment does not fulfil the quality requirement, it has to be decided whether there are enough financial resources to update the equipment or if it will be necessary to change the expected level of detail, which will then influence the final product.

Due to its apparent simplicity, the above described process of defining quality, equipment and finance, is often underestimated. In the context of information systems (chapter 6) and scientific visualisation (chapter 7), for example, the acquisition of too much data or data with a far too much detail often results in the need to reduce the acquired data. Valuable resources have been wasted only to realise at a later stage that it is not feasible to display such detailed data, since e.g. computer hardware cannot cope with the amount of data collected. However, it may sometimes be advisable to collect additional data, e.g. in situation where it is not possible to go back to the site and collect data at a later stage. Another problem encountered is that too little data, such as digital images with a low resolution have been acquired and the expected 3D displays cannot fulfil the requirements or accuracy. It is strongly advisable to design a pilot project to test the equipment and quality levels, even to the point of producing an example of the final product. One area that is not included in the discussion of the project requirements is the human factor. Availability and the level of expertise of specialists as well as the costs of employment are beyond the scope of this chapter since they vary for each individual project. After the project parameters are determined the detailed planning stages follow. The following chapter gives an overview on the choice of the photographic equipment, which influences the network design for the control points, the image acquisition plan and the estimation of the actual project costs.

5.2.1 Choice of photographic equipment

Since the purpose of the data acquisition is the creation of a digital product, i.e. the information system, the images have to be available in digital format. The use of digital cameras is becoming standard due to advantages such as the possibility of downloading images immediately, processing them on-line and storing the data easily in a compact format.

The photographic equipment can generally be chosen using the following parameters:

- focal length of the lens
- type of image acquisition (digital/analogue and colour/BW)
- resolution of the chip/film type
- in the case of analogue images: the scanner equipment

Digital cameras are not designed for photogrammetric purposes. They vary considerably in resolution, dynamic range (bit/colour channel), file size and price, and only a few cameras are suitable for fieldwork. Digital 'field' cameras can store images on a PCMCIA card in the camera, operate as stand-alone units, and do not require special lighting. These cameras operate in a similar manner to a 35mm film camera, with the image captured on a CCD chip rather than 36mm x 24mm film. They are also robust enough to withstand harsh conditions on site, e.g. dust, temperature changes, humidity.

The resolution of the digital camera chip cannot yet compete with the detail stored on film. But, as stated by Warner, the accuracies yielded from the lower resolution of the CCD camera chip prove suitable for photogrammetric applications (Warner et al. 1997).

In the latest digital camera series, where the shadow detail and colour range are improved, the image quality and camera geometry still need post-processing corrections. The chip occupies a much smaller area than the 35mm film for which camera bodies were originally designed and this alters the behaviour of the camera in two significant ways:

Firstly, as described by Warner, the small sensor more than doubles the effective focal length of the lens, so that a wide angle lens becomes a short telephoto lens. For example, the digital camera Kodak DCS420 fitted with a 28mm lens provides the same coverage as a 70mm lens with 35mm film (Warner, 1997), while the image scale differs by a factor of 3.

Secondly, the small array plays havoc with the in-camera metering. Fraser et al. (1995) observed this flaw with the light metering of the Nikon N90 and Canon EOS-1 camera bodies. Both bodies have sophisticated built-in metering that provides excellent exposures on film, but they are not well matched to the CCD (Fraser et al., 1995;Grotta and Grotta 1995).

Of greater concern is the questionable stability of the chip. Although a digital camera can be calibrated, instability remains a potential problem as for example in the Kodak DCS 420 camera. The chip is fixed to the camera body by a bolt running through the camera back, and is liable to move relative to the bayonet mount when the camera is moved. Since it is likely that the camera will be exposed to vibration or shaking in the field, a pre-calibration would not be stable enough to determine the interior orientation parameters. Thus it is recommended that self-calibration routines be used when images are acquired with a CCD camera (Beyer 1990; appendix 13.1.3).

For special applications it might be a better option to choose the combination of a film camera and a state-of-the-art high-resolution scanner. The production of analogue photographs and the transformation into digital images will take more time than taking digital images, but it is still advisable if the image is required for ortho-image production or any other visualisation of the original image. As reported by Baltsavias (1999) it is of utmost importance to analyse the scanner accuracy and performance. Insufficient geometric and radiometric scanner performance can cause severe problems. A detailed overview and comparison between different scanner models is given by Baltsavias 1999.

At this point in time the ideal solution for high resolution imagery would be to take large format photographs with an analogue camera on glass plates (to avoid film shrinkage) and to scan them with a high quality scanner. The next best solution would be to use film and scan the film negatives (to avoid distortion in the enlargement process). The level of detail and accuracy will deteriorate when a photograph hardcopy is scanned, and a comparison to the imagery of digital cameras still needs to be investigated.

After choosing the photographic equipment, the geometric design of the data acquisition follows. Details such as the distribution of control points, the layout of camera stations and overlap areas, have to be planned carefully to ensure a high quality product (appendix 13.1.4).

5.2.2 Geometric Design

One of the challenges associated with the development of a general methodology for documenting archaeological sites is that the requirements and specifications vary widely from site to site. Regardless of the nature of the photogrammetric measurement task, a common goal should be the maximisation of overall quality within the constraints imposed by these requirements and specifications.

In order to establish the position and orientation of each photograph in space relative to the object it is necessary to use co-ordinated control points, which are determined in the object co-ordinate system. Conventional survey techniques establish the position of the photogrammetric control points with respect to the reference co-ordinate system.

In optimising the measurement operation, usually in terms of accuracy and economy, particular attention must be paid to the quality of the photogrammetric control point network. The design quality of such a network can be expressed through a number of target functions such as precision, reliability and economy.

Precision is determined at the design stage through the choice of an observation scheme for the network. That is, through the network's geometric configuration and the accuracy with which the observations can be carried out.

The design for a close range photogrammetric network entails the following steps:

- definition of the number, position and orientation of camera stations
- definition of the optimal image scale
- definition of the overlap area
- determination of the number of photographs taken at each camera station
- assurance of adequate depth of field for sufficiently sharp focus
- design of targets and identification of which target will be captured in which image
- localisation of areas in the target array, where the accuracy will be weak due to network configuration or practical factors such as target distortion by image perspective

There are a few key issues that have to be kept in mind when the control point network is designed (Mason, 1995):

- The resolution of an object must be sufficient to support image measurement to the desired accuracy. The resolution is influenced by the focal length of the lens system, i.e. the ability to zoom and the pixel size on the ground, and impacts on both the target design and the image scale selection.
- Optimal positioning of the camera might not always be possible as a result of obstructions on the site, such as limited setback distances for the camera. This may influence the image scale selection, sometimes even the camera positioning. The use of wider angled lenses or the capture of additional images are means to overcome these workplace constraints.
- Since the precision of image measurement is influenced by the lens focus, the depth of field of the lens has to be taken into account during the planning stage.

- As described by Fraser (1984), the reliability of image measurement of planar targets, such as control points, decreases as the angle of incidence drops below a certain value. Different target features, materials and shapes influence the minimum acceptable incident angles. Spherical targets are the optimal solution, since they are not affected by incident angles. For near planar objects the depth of field constraint is often more restrictive than the issue of the minimum incidence angle (Fraser, 1984).

- Fraser (1984) also shows that the number of targets within a network has little impact on the precision of object point triangulation, as long as there is a sufficient number in each image to support exterior orientation. However, the statistical reliability of the orientation can be expected to be enhanced through the greater redundancy of observations as well as the precision of the recovery of the self-calibration parameters (appendix 13.1.2).

CAD-based and interactive computer simulations for close-range photogrammetric networks have been successfully employed in design optimisation. The methods employed for these simulations can follow a number of approaches. Generally, the accuracy specifications are established first and then an observation scheme is adopted. This procedure may entail the selection of a particular camera for the survey, the post-processing equipment to be used, a first approximation of the imaging geometry and the number of all control points appearing in the images.

The results of the network design are translated into the image acquisition plan, which combines all field activities in one plan layout.

5.2.3 Image Acquisition Plan

The image acquisition plan gives an overview of the necessary data acquisition in the field by creating an outline of the procedure. In an archaeological environment, where there might only be limited time available for data recording due to ongoing excavation or conservation tasks or other obstacles, it is very important to establish a good field plan, especially if the object to be mapped is of a complex nature.

The image acquisition plan is based on the results of the geometric design. The main elements shown in the plan are the position and orientation of the camera, the camera-object distance, the distance between successive exposures (base line), the focal length of the lens, image width and height, image scale, the ground cover of the image, a relative positioning of the targets and the overlap of the images.

The plans can be done in a graphic or a tabular form. Graphic plans or maps that show the site and the planned control point layouts and overlaps have the advantage of presenting a visual overview. Tabular forms are very popular since modern spreadsheet software packages are making it increasingly easy to set up a number of scenarios before implementation and then choose the most appropriate one for the situation.

IMAGE ACQUISITION PLAN

	DCS	DCS	DCS	UMK	UMK	UMK
Control interval lateral	0.90	0.90	0.90	0.90	0.90	0.90
Base line	0.30	0.30	0.30	0.30	0.30	0.30
Focal length [mm]	14.5	14.5	14.5	100.0	100.0	100.0
Image width [mm]	13.5	13.5	13.5	155	155	155
Image height [mm]	9.0	9.0	9.0	110.0	110.0	110.0
Camera height	1.60	1.50	1.70	1.30	1.20	1.40
Image scale 1:	110	103	117	13	12	14
Ground cover WIDTH	1.5	1.4	1.6	2.0	1.9	2.2
Ground cover HEIGHT	1.0	0.9	1.1	1.4	1.3	1.5
Overlap	1.2	1.1	1.3	1.7	1.6	1.9
Centre interval	0.90	0.90	0.90	0.90	0.90	0.90
left edge left image	-0.30	-0.26	-0.35	-0.57	-0.49	-0.65
left edge right image	0.00	0.04	-0.05	-0.27	-0.19	-0.35
Control West	0.14	0.14	0.14	0.14	0.14	0.14
Camera West	0.44	0.44	0.44	0.44	0.44	0.44
CENTRE	0.59	0.59	0.59	0.59	0.59	0.59
Camera East	0.74	0.74	0.74	0.74	0.74	0.74
Control East	1.04	1.04	1.04	1.04	1.04	1.04
right edge left image	1.19	1.14	1.23	1.45	1.37	1.52
right edge right image	1.49	1.44	1.53	1.75	1.67	1.82

Figure 7 Example of an acquisition plan spreadsheet

Figure 7 shows a number of different scenarios employing a DCS 420 camera and a UMK camera. The base line is chosen with 0.3 m for both cameras, and the lens systems used have a focal length of 14.5 mm for the DCS 420 and 100mm for the UMK. Image height and width are known. There are three different camera heights for each camera, showing the changes in scale, ground coverage and the overlap, allowing the choice of the most suitable one.

Figure 8 shows an example of a graphic image acquisition plan, indicating the different overlaps, control points and object to be identified within each image.

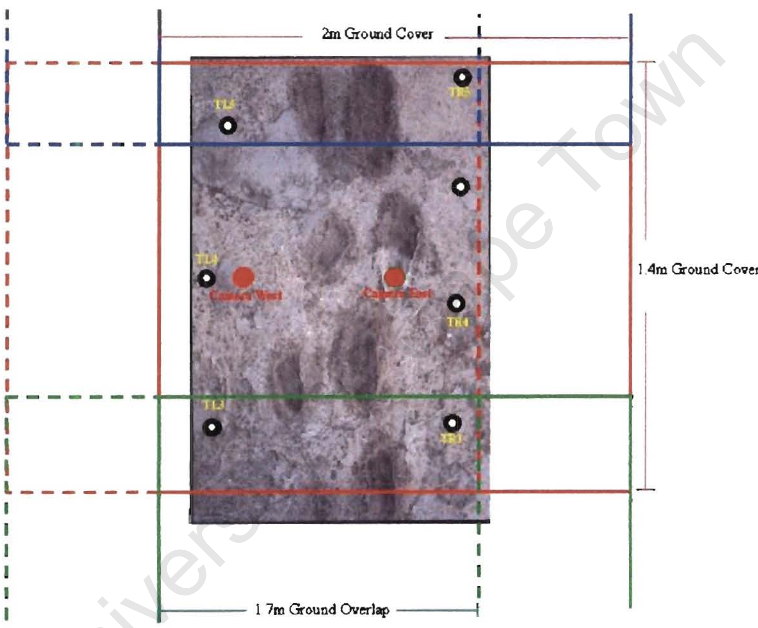


Figure 8 Example of a graphic image acquisition plan

Besides discussing the detailed tasks of data acquisition in the field, the time schedule must be reviewed when formulating the image acquisition plan. The most time-intensive section of the data acquisition on site is the determination of the co-ordinates of the photogrammetric control points using conventional surveying techniques. Since the number of control points is directly dependent on the ground coverage of the images (appendix 13.1), which result from camera-object distance, image size and focal length, a re-evaluation of the project requirements might sometimes be necessary. In the case of a tight time schedule, it can be advantageous to consider using different angle lenses or to increase the camera distance, so that the image covers a wider area on the ground. This will influence the resolution of the images and the accuracy of the acquired data.

5.3 Stage 2: High Precision Survey of Control Points

The position of the photogrammetric control points relative to the object co-ordinate system is generally determined by a high precision survey, which has two field components:

- establishment of a datum (reference co-ordinate system);
- conventional high precision survey of photogrammetric control points on the ground

A common reference system is used for all surveys and mapping activities on site. This allows different data sources such as maps and local field surveys to be combined for visualisation purposes.

Round, retro-reflective targets are often designed as photogrammetric control points to allow the automatic extraction of the targets for orientation purposes (appendix 13.1.3). These designs can be a challenge for a precision survey carried out with theodolites, since it might be difficult to aim at the disc centre with sufficient accuracy. The following observation sequence can be adopted to measure the round targets successfully and to establish horizontal and vertical angle combinations for target positioning:

1. Bottom left (blue corner) - horizontal (1) and vertical (2) angle measurement
2. Top right (red corner) - horizontal (3) and vertical (4) angle measurement

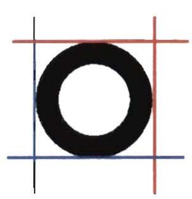


Figure 9 Measurement of Target

The mean of observations 1, 2 and 3, 4 provide an angle observation to the disc centre in horizontal and vertical directions respectively.

In a sensitive archaeological environment it is often not possible to use staves or levels for height measurements of control points. Vertical angle measurements can be used instead and generally satisfy the accuracy requirements.

The figure below shows a network setup for a control point survey.

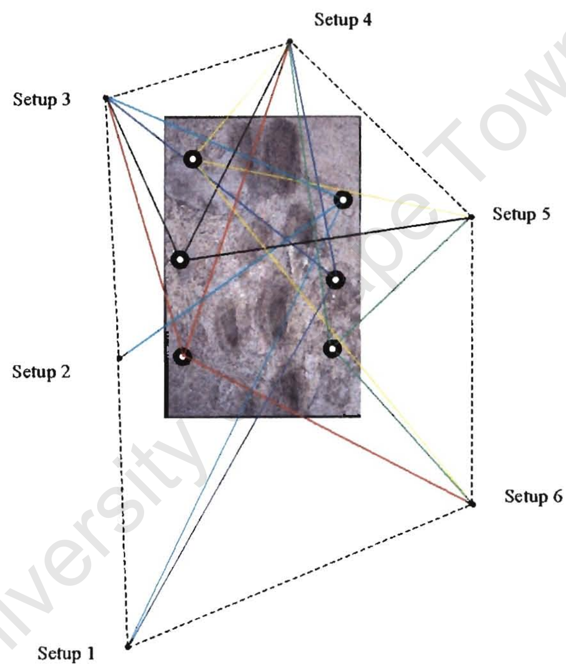


Figure 10 Scheme of a photogrammetric control point survey (rays of reference network are not shown)

Once the control point positions are determined and the acquisition plan is laid out, the images are acquired.

5.4 Stage 3: Photogrammetric Data Acquisition

The difficulty – and thus the challenge – of archaeological survey projects is the large variety of possible objects and their sizes and positions. Resulting documents may be scaled between about 1:1 and 1:1000. Archaeologists generally produce drawings for their documentation within sight of the object and with the aid of simple instrumentation such as rulers, measuring tapes, string grids, and levels. Photographs, not intended for photogrammetric processing, complete this kind of documentation.

Photogrammetric data acquisition has a different motivation than merely taking pictures. The following points indicate the most important aspects that should be considered when acquiring imagery in the field.

Archaeological objects can have rather complicated shapes and may either be very small or very large (in a close range context). If representations of objects having full 3D extent are necessary, as in the case of statues for example, the images have to be taken in a manner to allow the creation of an all-round view. The object model can then be virtually re-created by piecing the various views together.

It is important to acknowledge the purpose for which the recording procedure is designed. For creating the basis of a three-dimensional model, the images do not have to look "pretty". Photographs taken for documentary purposes often use shadows to create special effects. Images taken for photogrammetric purposes should not have too much shadow, as the quality of the information will be compromised due to the loss of information in the shadow areas.

As described in chapter 5.2.1, the light meter of digital cameras should be tested before taking photographs. Images taken with the Kodak DCS 420 proved to be underexposed when program mode (automatic setting of aperture and exposure) was chosen. The chip is less sensitive to light than the film according to histograms of images taken in different situations. Therefore it might be advisable to allow some testing time on the site for establishing the right light meter settings.

For image acquisition, the focus ring of the lens must be taped down once the camera is focused at the appropriate distance. Ideally, the aperture setting should also be held fixed at the most appropriate stop. Varying the aperture may result in distortions of the incoming light rays, causing changes to the interior orientation parameters (appendix 13.1.3).

It is important to check what the camera captures before the image is taken. This can be rather difficult if the camera is high above the ground and it is difficult to get to the viewfinder to see what will be recorded. Sometimes it might even be necessary to process the photographs in the field to control the coverage of the images, which is not a problem with digital cameras but can be rather challenging with film cameras.

It is also advisable to keep a good written record of each photograph including the lighting conditions at the time, the aperture, focal length, height of the camera, and exposure. These records can be used as references for the image processing later on.

The following flowchart gives an overview of the image acquisition process. It shows the differences between analogue and digital cameras and marks the steps that need to be taken to ensure successful coverage of the site. It is advisable to develop a checklist for the site work due to the repetitive nature of the process and to minimise human error.

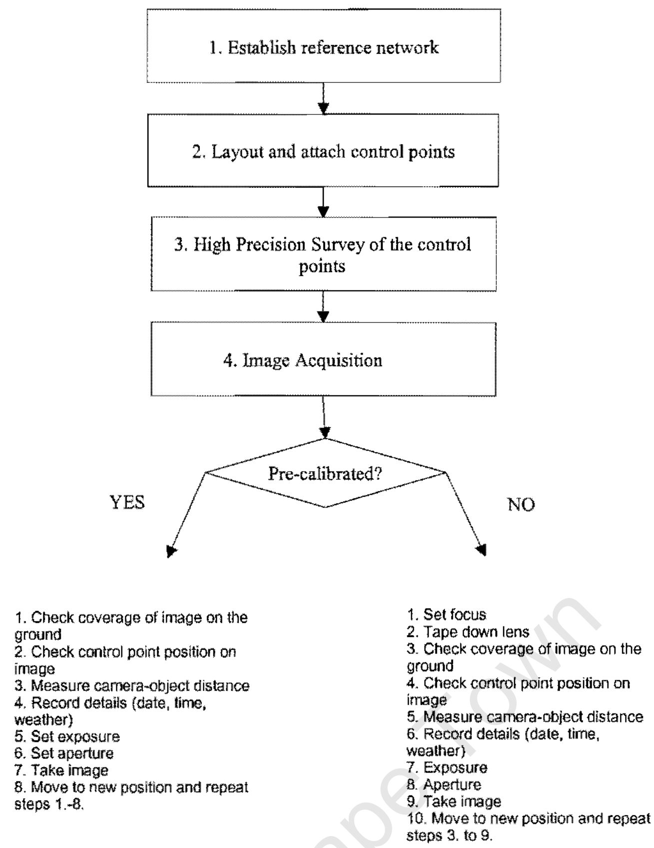


Figure 11 Image acquisition in the field

5.5 Stage 4: Photogrammetric Data Processing

After the images are acquired in the field, a number of post-processing activities have to follow before the images are in a format that allows 3D-object reconstruction. The following chapter gives an overview of a typical approach for the creation of reliable data that can be used as the base data for the database of the information system and the visualisation tools.

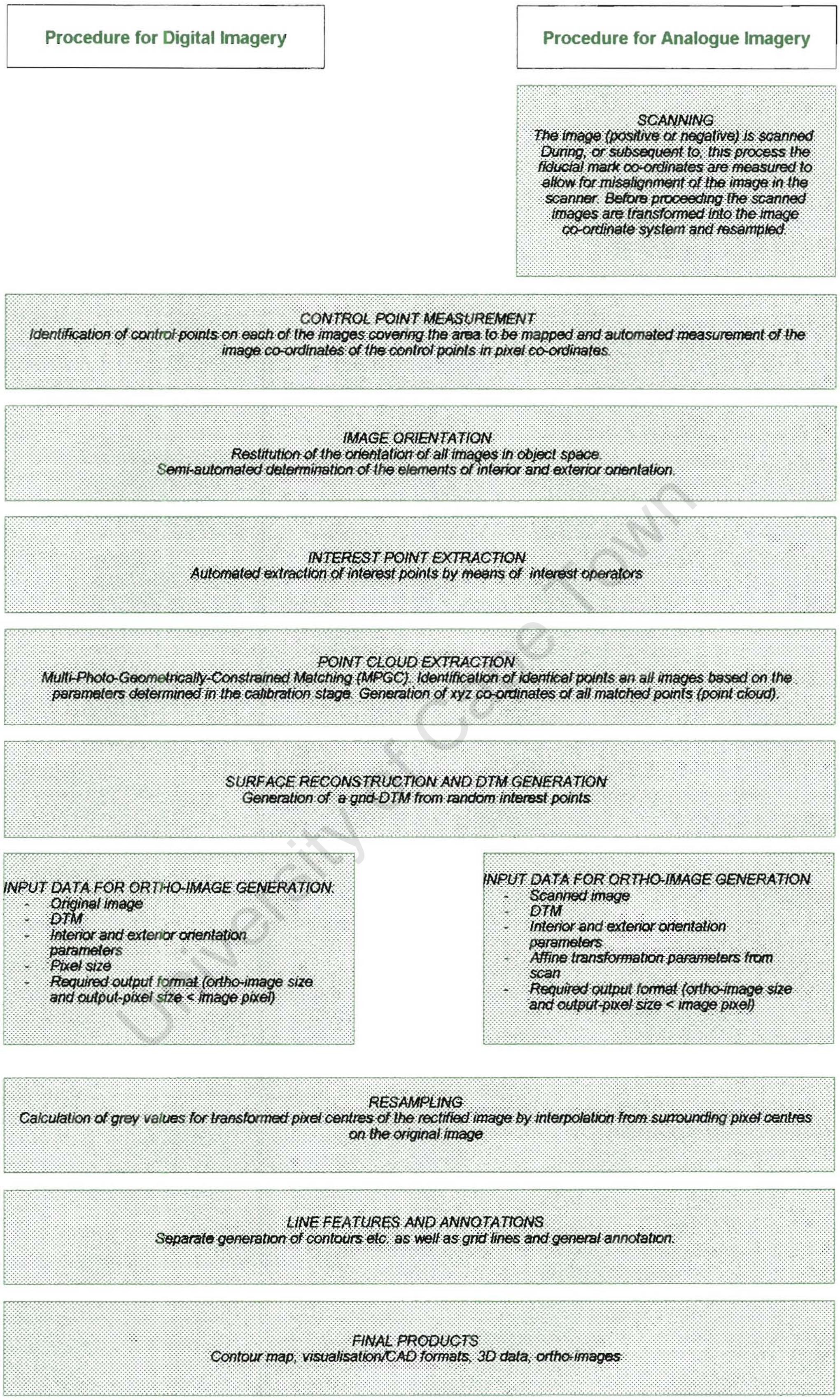


Figure 12 Post-processing procedure of photogrammetric data

The flow chart shows an ideal scenario, where all the data is available in the right formats and the necessary software exists. However, in a real world scenario a number of added complications are generally introduced by the constraints of hardware and software, the equipment, different co-ordinate systems, and so on.

In general it is advisable to work in a consistent setup. This means that a strict policy should be developed to force all the data to be processed in the same way. Otherwise it will be difficult to trace data errors and to ensure the overall accuracy of the system. Digital photogrammetric processing software allows images to be rectified without human interpretation, as opposed to the analogue setup where an operator is required. An automated process will therefore have less of a bias, which is important if the data is used for further research. One of the drawbacks of automated processes is the problem of outliers, which can be created by wrongly matched points (appendix 13.1.5). These outliers have to be inspected by an operator and removed by hand or automatically. This process can be rather time consuming.

At this stage there are only a few photogrammetric software packages commercially available that offer a 'black box' approach to the ortho-image generation of close range applications. Commercial digital photogrammetry software is generally designed for aerial imagery, but some offer an option for close range applications. In these packages the acquired images have to fulfil a number of requirements as described by the individual package manufacturers and may not always be suitable for specific applications, such as archaeological sites.

The general ortho-image package allows the user to follow an automated sequence, which leads even the untrained person to the result. The differences between the software packages of different distributors lie in the processing algorithms, data input, stereo viewing capabilities, possible extension, image formats and so on. The following sub-chapters concentrate on the requirements necessary to produce ortho-imagery.

It is important to note at this stage that these subchapters are not specific to any software, but give an overview that applies to any commercial or in-house package.

5.5.1 Recovery of Orientations and Surface Reconstruction

After the images are downloaded and stored in an appropriate format, the interior and exterior orientation parameters have to be recovered (appendix 13.1.2). As discussed in chapter 5.2.1, images that are acquired with digital cameras should be oriented using a self-calibration for each model. Metric cameras, like the ZEISS UMK camera, have pre-determined interior orientation parameters and self-calibration is only applied if changes occur.

To recover the interior orientation parameters, the established control points have to be measured in the images. The digital images are displayed on a computer screen and control points are identified on each of the images covering the area to be mapped. This can be done by an automated search routine if the control points are well defined and a suitable search routine is available.

A best case scenario for automated target recognition is given in close-range photogrammetric applications where the environment can be controlled and targets can be clearly (visually) separated from the background or object. This should be considered when the targets are designed.

If conventional photographs are scanned (e.g. UMK images), they need to undergo an affine transformation via fiducial marks to allow for misalignment of the photograph in the scanner. This is also sometimes referred to as inner orientation.

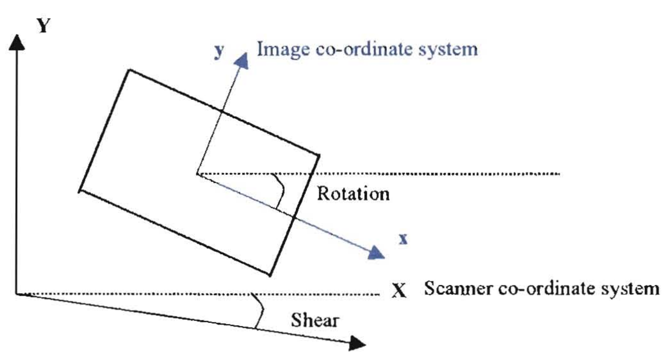


Figure 13 Affine transformation from scanner to image co-ordinate system (x-shift, y-shift, x-scale, y-scale, rotation and shear)

For non-metric cameras the image corners serve as the definition of the image co-ordinate reference system. Any shear deformation of the chip as well as the pixel size is generally accepted as being constant and can be determined in the calibration process. There is no rotation because the pixel array on the chip is used as the reference system and thus the directions of the axes automatically coincide with the pixel lines. However, it is necessary to allow for the differences between the image co-ordinate system and the chip/pixel co-ordinate system (Figure 47).

The orientation process in most photogrammetry software packages is based on a bundle adjustment and requires the following input values:

- the elements of the interior orientation (unless they are to be determined as part of the solution, in which case good provisional values must be provided)

- the image co-ordinates of the control points in units of pixels or millimetres. If the data is in pixel units, then the pixel dimensions and the affine shear of the pixel array must be provided (assuming that the software can correct for affine distortion)

- the object space (XYZ) co-ordinates of the control points

- the provisional values for the exterior orientation parameters

The results are usually the adjusted orientation parameters (ϕ, ω, κ, X_0, Y_0, Z_0) and the interior orientation elements (x_p, y_p and distortion parameters), if included in the model as unknowns as well as the standard deviations (variance co-variance matrix) of the adjusted parameters.

After the orientation parameters are established, the points of interest have to be extracted from the images.

In order to obtain surface points, an interest operator is applied to the images to find the image points which differ radiometrically (i.e. in appearance) from their immediate neighbourhood automatically. Such points are typically edges, texture, corners, etc., which are representatives of the surface. Different software packages use different operators. Some of the commercially available packages do not offer interest point detection as an individual step, it is combined with the automated matching process. The operator only has to define the area within which the surface of the object must be created. It has to be stressed that for high accuracy applications it is very helpful to be able to choose the algorithms the software uses.

5.5.2 Surface Reconstruction, DTM Generation and Ortho-image Production

The determination of point positions in order to reconstruct a 3D surface from 2D images is based on the identification and measurement of image points from the same object on two or more images. The rays formed by the 'conjugate' image points and their respective perspective centres are intersected. The photogrammetric model known as the collinearity condition is used for the intersection of conjugate rays in object space (appendix 13.1.2).

A very effective method for the automatic detection of conjugate or matching points is the Multi-Photo-Geometrically-Constrained-Matching (MPGC) technique (Grün et al 1989), as described in appendix 13.1.5.

A number of commercially available packages allow for automated matching, but it is not always clear which algorithms have been used to determine the 3D information. It is important to ensure the integrity of the software package by investigating these.

The process of surface reconstruction is usually the generation of a regular grid from a random point cloud. This is done by the interpolation of point heights for the grid points at a pre-selected grid interval. The height of each of the grid points is interpolated from the points of the point cloud in its immediate vicinity. Generally, the software allows the user to choose from a number of algorithms, which are applicable for different terrain. The most popular are: nearest neighbour, bilinear, bicubic splines, or Lagrange Interpolation.

Due to the properties of perspective projection, point positions on a photographic image differ from those on a map, which is an orthogonal projection (appendix 13.1.6). The quantity and the direction of displacement depends on the elevation of the object points above the chosen reference surface, the elements of the interior orientation of the camera, the position and orientation of the camera, and any systematic image distortions (e.g. lens distortion). If all these quantities are known, then each point or pixel can be moved into its orthogonal projection position.

The surface models and the ortho-images reconstruct the object. This spatially correct data can now be used either as a final product and presented in map-format, or it can serve as the base data for visualisations and spatial information systems as shown in Figure 14.

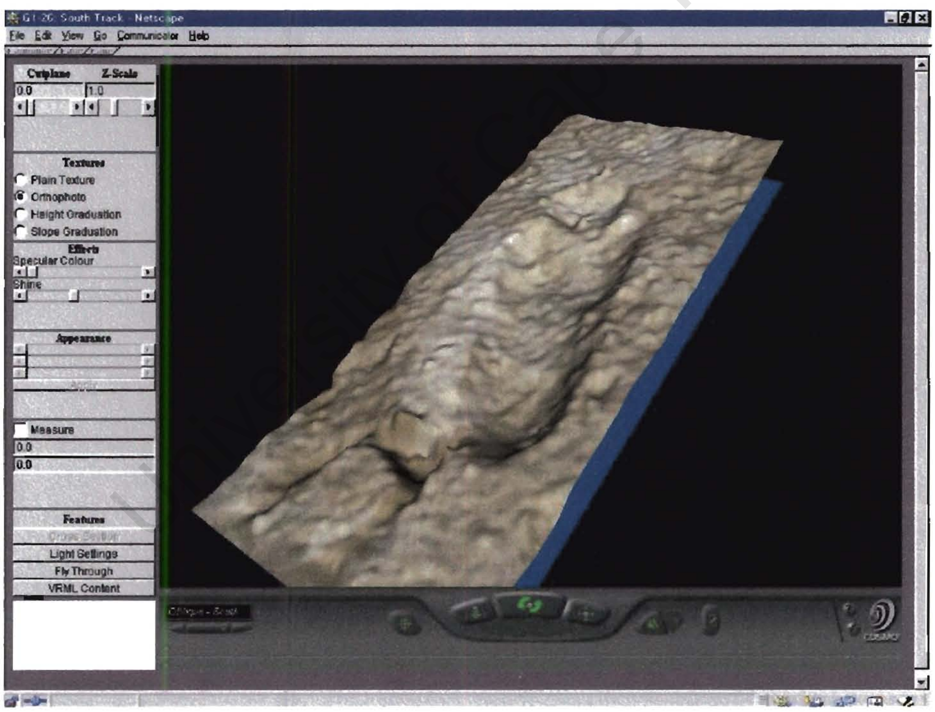


Figure 14 Overlay of Ortho-Image and DTM

5.6 Summary

The objective of this chapter was to introduce the approach of data acquisition by means of close range photogrammetry with the view of using the data for the creation of an integrated spatial information system.

It was shown that a successful data acquisition requires detailed project planning, which is mainly determined by the purpose that the data is to fulfil. The quality parameters, the equipment used and the finances available have to be established by keeping the constraints and objectives of the project in mind.

The choice of the photographic equipment is dependent on a number of factors such as focal length, resolution and chip stability. For the latter the self-calibration approach was offered as a solution. It was also recommended that light meters and chip sensitivity be tested to ensure no data is lost due to over- or under exposure.

In the design of the geometric network, the number of camera stations, image scales, design of targets, depth of field and the number of images were determined. Key issues, such as resolution, camera positioning and precision of measurements were explained.

The image acquisition plan finalised the planning stage by creating an overview of the tasks that need to be executed in the field. Important factors such as time planning and economic reduction of data acquisition were introduced.

By introducing the main features of commercially available ortho-image packages, the photogrammetric data processing was explained, discussing the recovery of image orientation, surface reconstruction and ortho-image generation.

In conclusion it can be said that data acquisition using digital photogrammetry does not fail in harsh conditions on site. It satisfies all the requirements of producing high quality data in an economical way. Alternatives to the approach, such as Laser Scanning, have not yet been sufficiently tested on remote archaeological sites to be considered as a reliable alternative to close range photogrammetry.

6 Data Management using an Integrated Spatial Information System

Developments in information technology over the past decade have lead to an increased use of digital data and processing techniques. This is becoming especially prominent in the field of archaeology, which utilises such advantages of digital imagery and digital products as:

- the integration of data into information systems,
- the automation of complex procedures, e.g. DTM generation, and
- the possibility of a direct interface between visual products and information systems

The price deflation in hard- and software for PCs that, when equipped with powerful processors and video/graphics cards, can perform tasks that previously required highly specialised hardware, has encouraged the wide use of digital processes.

The collection and production of enormous quantities of data is a general issue within any collection process, but this has become aggravated with the use of digital systems. An attitude of "the more, the merrier" has evolved for a number of reasons, e.g. the lower financial implications of digital image acquisition compared to analogue photographs (i.e. costs of film, development process, etc.). Bitelli (1997) discusses that discernment of which data is actually needed is sometimes lacking and often the data (e.g. images) is acquired without the necessary information describing the data (i.e. meta data), which may make it unusable for processing, or may prevent the data from being used in the future by others. Thus the need for a controlled process of data acquisition and a management system for the organisation of the data is fundamental.

In general, the potential of using data incorrectly has increased in the same way that technology has improved. Bernhardsen (1999) states, that the 'black box' approach adopted by software manufactures for non-specialists using specialised software can turn out to be more expensive for a project if it is not clearly defined what data is needed and how it should be acquired and managed to obtain the required product.

The following chapters give an overview on how to manage, organise, store and retrieve spatial data, with a focus on data specifications, requirements and feasibility studies.

The generic issues surrounding the development of information systems will be discussed, i.e. strategic planning, situational analysis and the Integrated Spatial Information System (ISIS) project planning. Different possibilities for the design of such an information system dependant on philosophy, function and technical standards are presented and evaluated.

The flowchart below shows the creation of an ISIS, using the data acquired by means of close range photogrammetry.

After a general introduction to Information Systems a methodology for the development of an ISIS will be introduced from chapter 6.3 onwards.

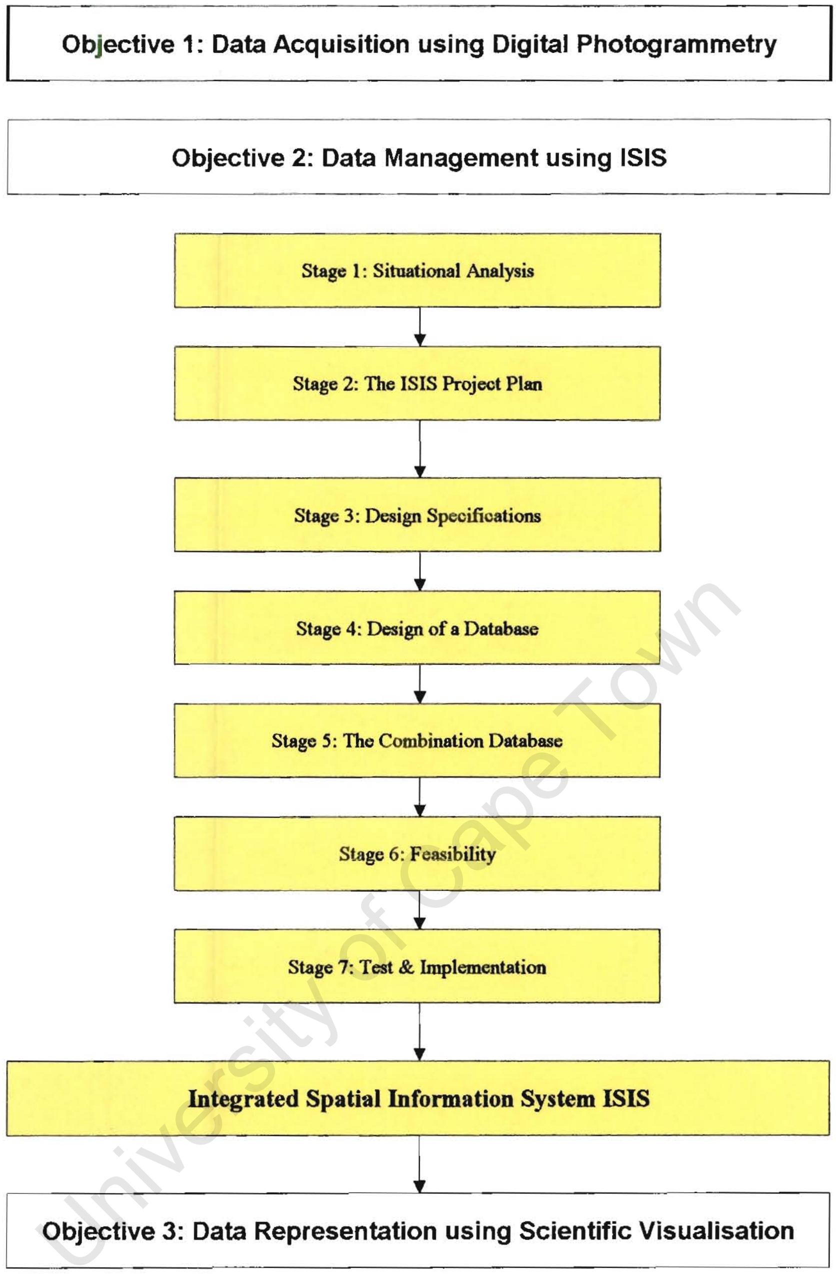


Figure 15 Chapter Overview

6.1 Information Systems as a Data Management Tool

To design an Information System that will be accepted by its users, an awareness of possibilities, trends, expectations and limitations of information technology is essential. This chapter focuses on developing a satisfactory definition and deriving the fundamental principles on which Information Systems are based.

Statements like "Management is what differentiates success from failure" (Longley 1999) make it clear that management must play a principal role for a project to be successful. For the purposes of this thesis, the term "management" shall be used in the context of the design of an information system and is defined as the organisation and administration of data accordingly to a set of rules.

An Information System (IS) is a system for capturing, storing, checking, manipulating, analysing and displaying data. The focus is on the analysis of the data, and includes for example decision-making processes, the creation of 'what –if' scenarios and the possibility of combining different data sets.

Information systems are usually understood to be computer-based systems for handling digital data and are composed of four major sub-systems:

- A data entry subsystem for handling the translation of raw or partially processed data.
- A data storage and retrieval subsystem which accepts the input stream from the data entry subsystem and structures the database for efficient retrieval.
- A data manipulation and analysis subsystem which executes all data transformations initiated by the user.
- A data visualisation and reporting subsystem which returns the results of queries and analyses to the user.

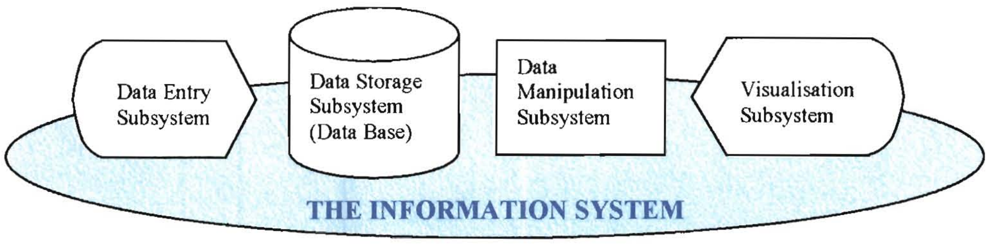


Figure 16 The Information System

The term database refers generally to the data storage and retrieval subsystem and should not be confused with the Information System as such.

The above mentioned components will not always have the same emphasis. The system developer must establish whether the IS will serve as a transaction processing system with a focus on recording, or as a decision support system with the emphasis on analysis and modelling of data. In this respect it is important to define the requirements of the IS. In some situations it might be necessary to emphasise various components of subsystems to allow flexible data handling.

Most software developers of IS advertise off-the-shelf packages for data management. As mentioned by Bernhardsen (1999) there is unfortunately no 'off the shelf' solution for every project, since each data management and information system is an individual system, which serves a specific function in a specific organisation or situation. The importance of making strategic decisions on the emphasis of an IS cannot be underestimated. These decisions will determine whether a successful, well-established and accepted data management system is created.

6.2 An Integrated Spatial Information Systems (ISIS) in an Archaeological Context

Information systems are seen by an increasing number of archaeologists as being the information technology to be adopted for location analysis, spatial data management and spatial modelling (Kvamme 1992). This chapter shows why an archaeological IS has to be designed in its specific context and why it is not an off-the-shelf product.

Due to the rapid development of commercially available Geographic Information Systems (GIS) the first data management systems used in an archaeological context were the popular GIS packages.

GIS represent reality as a multi-layered series of geographically referenced features. The geographical data is used to provide a reference for the objects instead of the attribute element and this differentiates GIS from other Information Systems.

Strictly speaking, the term 'geographical' refers only to locational information about the surface or near-surface of the earth. In archaeology data is generally spatially referenced, but this reference may not necessarily be geographic. For example, an artefact found on an archaeological site would be defined by its location relative to the site co-ordinate system in a GIS, represented for example by the co-ordination of one point on the artefact. If the artefact is re-constructed in a 3D-visualisation application, the object co-ordinate system may be arbitrary and possibly conflict with the co-ordination of the artefact in the GIS. If objects are represented within the same IS in different co-ordinate systems, the IS has to be flexible enough to deal with this kind of double referencing.

In general, the use of the term 'spatial' in an IS context refers to data linked to a location derived from primary or secondary surveying measuring operations. An information system that combines information of a spatial and attributive nature and allows the integration into a system higher order (e.g. the Internet) is defined as an Integrated Spatial Information System (ISIS).

For specialised applications such as archaeological ISIS, the combination of commercially available software packages will not necessarily provide all the tools. Sometimes it might be necessary to program modules, which are then embedded in the ISIS. For example, if there is a need to search information contained in a text document, it is appropriate to use a word processing package and have a link established from the ISIS application to the word processor. Another example is the previously mentioned data representation. Visual data displays in commercial GIS software packages are designed to serve mainly the geographical aspect of data representation and this may not be sufficient for the archaeological site. Since it is easy to connect a more applicable 3D or CAD package to the

ISIS software by using graphical user interfaces (GUI) and links, the combination of three or four application software packages increases the functionality of the overall system.

However, the design of the information system and its database should be flexible enough so that software developed in the foreseeable future can be incorporated and implemented without major re-design.

An archaeological ISIS must be founded on archaeological methods and concepts. The system represents the ordered integration of archaeological and related data into a common administrative and research unit in order to facilitate the research and management of cultural heritage sites.

The ISIS should comprise past and present archival and bibliographical data, survey and site data, excavation reports, studies and analysis, finds and museum data, and conservation information, and should provide easy access to complementary information where necessary. To be successfully established, it must be organised and structured in such a way as to encompass relevant facets of archaeology. Archaeology is usually defined as the scientific study of human chronological and historical evolution through the study of historical remains and traces left through time. Thus it is important for the development of an archaeological ISIS that a spatio-temporal aspect is included to analyse data in this dimension (Gillings 1996, Allen 1990). The introduction of the fourth dimension requires the development of a module that can handle four dimensions and that allows the display of these complex data sets.

It is important to guard against the development of an information system merely as an unintelligent tool. This would be under-utilising the potential and ignoring the need of simultaneously developing an IS culture. An ISIS, in the form of a data management system for data recording, analysing and visualisation, must be seen as a medium of archaeological analysis capable of generating models of explanation.

6.3 Design of an Archaeological ISIS

Information systems are not developed in isolation, but often within the context of an institution. Independent of the size, mission, or profitability of the institution the information system will be introduced into an existing environment and expected to fulfil certain tasks. Archaeological institutions have a different focus compared to large corporations, but the issues they will face when designing and implementing an information system are very similar. In this thesis the word 'organisation' is defined as a formal or informal group of people (generally with a common interest in archaeology), e.g. conservation institutes, archaeological departments, non-profit organisations (museums).

For the design of any kind of information system, a number of key issues have to be addressed:

- The information in the system must be organised so that it will be meaningful when retrieved;
- Access to information in the system must be managed and carefully regulated;
- There must be continued support and maintenance of the information and technology within the system over time;
- The users must be trained and encouraged to use the system.

These requirements have to be addressed during the design stage of the system, to allow for a design representing the situation in which it will operate.

The first and main task in the development of an ISIS is the establishment of the vision, mission, strategy and policy of the organisation. Strategies are based on visions that articulate what direction the organisation has chosen for its future. Since the ISIS is implemented to assist achieving this goal, a mission for the ISIS can be formulated to express whether it will be, for example, a 'high quality data provider' or a 'basic infrastructure widely available to all users'. Once the mission has been determined, a strategy can be developed that represents the step-by-step plan to fulfil the mission.

The strategy plan should answer the following questions:

- What are the overall objectives of the new system?
- What tasks will the new system address?
- Who will use the system?
- What is the functional scope of the system?

After the strategy has been established, it will be translated into ISIS policies. These policies, if applied correctly to the design of the ISIS, will ensure a high quality product that fulfils the needs of its users and represents the organisation in its design.

The following flowchart shows the strategic plan for the design of an ISIS, followed by an explanation of the steps involved.

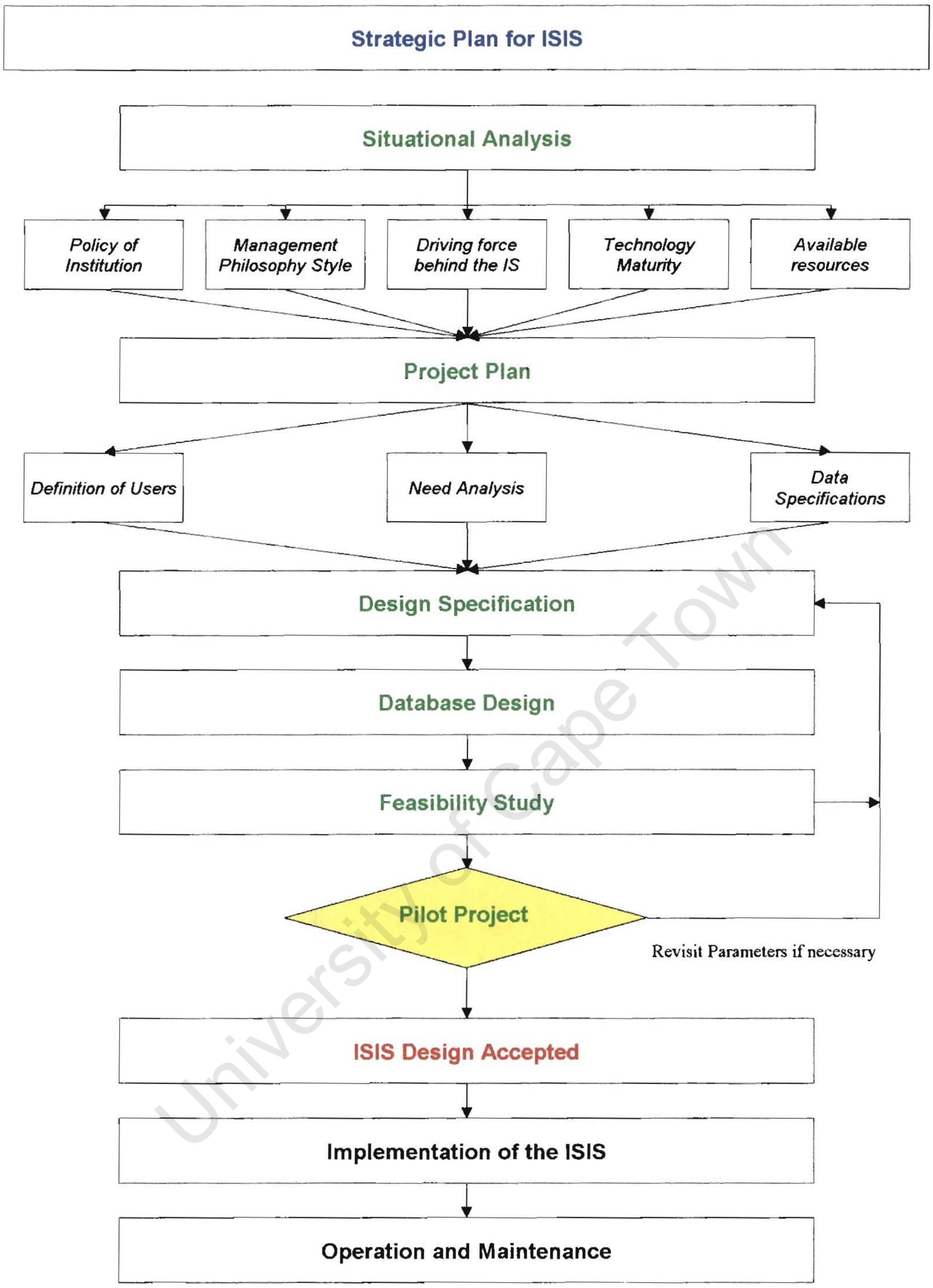


Figure 17 Strategic Plan for ISIS

The purpose of a *Strategic Plan* is to create a framework within which the complexity and interdependence of the ISIS design and implementation can be managed.

The phases leading up to the actual ISIS design comprise several steps, such as situational analysis and project plan. These steps may have different weights and – according to the policy established - may be either flexible or firmly established.

The phases leading up to the actual ISIS design comprise several steps, such as situational analysis and project plan. These steps may have different weights and – according to the policy established - may be either flexible or firmly established.
The *Situational Analysis* defines the organisation's philosophical, technical and resource situation at that moment in time and represents a crucial part of the *Strategic Plan*, because the ISIS has to be successfully implemented into an existing situation. The status quo of the situation is evaluated and a general concept is developed which will serve as a policy for the design.

The *Project Plan* establishes what is required on the basis of the *Situational Analysis*. It identifies the future users, analyses the needs and specifies the data requirements.

The *Design Specification* is based on the outcomes of the *Situational Analysis* and the *Project Plan*. This phase in conjunction with the Database Design, Feasibility Study and the Pilot Project needs to be seen as an iterative process pending the outcome of the Pilot Project.

The ISIS *Pilot Project* is a testing phase for the design specifications that have been established. Often it is useful to set up a pilot project to test the functionality of the system, applications, data transfer and the system integration, and to identify system faults.

The *Implementation* of the ISIS within the organisation and the *Operation and Maintenance* plan are the last steps in the Strategic Plan, ensuring that the system will be used to its full potential and maintained into the future. The initially established ISIS policies have a high impact at this stage, since future use and maintenance is difficult to control and will need to be re-enforced.

The following sub chapters give an overview of the different stages of the ISIS development from the situational analysis to the implementation stage.

6.3.1 Stage 1: The Situational Analysis

The primary premise of a situational analysis is that, in order to design and implement an ISIS effectively and to successfully operate and use it subsequently, the environment into which the technology is being implemented must be understood.

The secondary premise is that the person using the system has to be the most important factor in the design of the ISIS. Only if the system is well matched to the characteristics of the organisation, its mission, its operation, and its staff, will an environment of enthusiasm and innovation be created.

The issues, which have to be addressed in this context, concern the implementation of an ISIS in the working environment and the structure of the organisation:

- **Policy and mission of the organisation**

  - Which aspect of the organisation's mission impacts on the ISIS and how can this be reflected in the design of the ISIS (e.g. conservation and/or documentation oriented)?

- **Management philosophy and style**

  - How must the ISIS be structured to reflect the management, philosophy and style of the organisation?

  - Who is in control of the planning and design stage of the ISIS (one individual, a group, a department or a group of departments)? Is there a hierarchy regarding the impact of individuals/departments on the design and content of the ISIS?

  - Who besides the controlling body will be involved in the design of the ISIS?

- **The policy of the organisation regarding dissemination of information**
  - Who has access to the ISIS? Who can use the data? Who can modify the data?
  - Will the data be grouped in domains allowing different types of access to different parts of the database for different users?
  - Linked to the above, will there be selective access to the tools of the ISIS (e.g. can a specific data set be seen and changed by all users)?
- **Driving force for the ISIS**
  - Who champions the ISIS and guarantees continuity?
- **Technology maturity**
  - Is the staff sufficiently prepared for an ISIS?
  - Is additional training necessary?
  - How many staff use IS software already and how many of these can produce macros for the IS?
  - Would the users favour command-driven or icon-based approaches?
  - Will an ISIS be accepted and used throughout all levels of the organisation?
  - How long will it take for the organisation to adapt to the ISIS?
  - Will the ISIS concept be used for other projects?
- **Available resources**
  - How will the available resources (funds and people) be used for the project?

- **Relation to other organisations and institutions**
  - What deliverables for other organisations are expected from the ISIS?
  - What input from other organisations can be expected (data format)?
  - Is there any sensitive data?
- **Assessment uncertainties and risk factors in the design stage**
  - Communication plan (e.g. regular meetings)
  - Allocation of responsibilities
  - Authorities in the decision making process

Addressing these 'socio-technical' issues emphasises the need to match the requirements of the social system formed by people who will work with the system and the technological requirements for implementing the information system. The management team of ISIS developers and the organisation should have a defined set of responsibilities, describing in detail who is responsible for what task and how these tasks are defined. Different perception, especially in the case of two different types of specialists, such as archaeologist and system developers, can cause unnecessary misunderstandings and communication between the parties is therefore absolutely essential.

After the abovementioned factors have been discussed, a more detailed project plan can be established based on the defined policies and analysed situation.

6.3.2 Stage 2: The Project Plan

The Project Plan represents the first operational step of the strategic plan. It defines the fundamentals for the design of an Information System in the context of its environment and shows in detail what the system will do, rather than how the system will be organised.

The outcome of the project plan should answer the following issues (Zwass 1992):

- What outputs will the system produce and what input is consequently needed?
- What processing steps are necessary to transform the inputs into outputs?
- What data storage levels will have to be maintained by the system?
- What volumes of data will be handled?
- What number of users in various categories will be supported and in what fashion?
- What control measures will be undertaken in the system?

There are a number of different tools to gather the information needed to perform a complete analysis of the requirements (after Davis 1981):

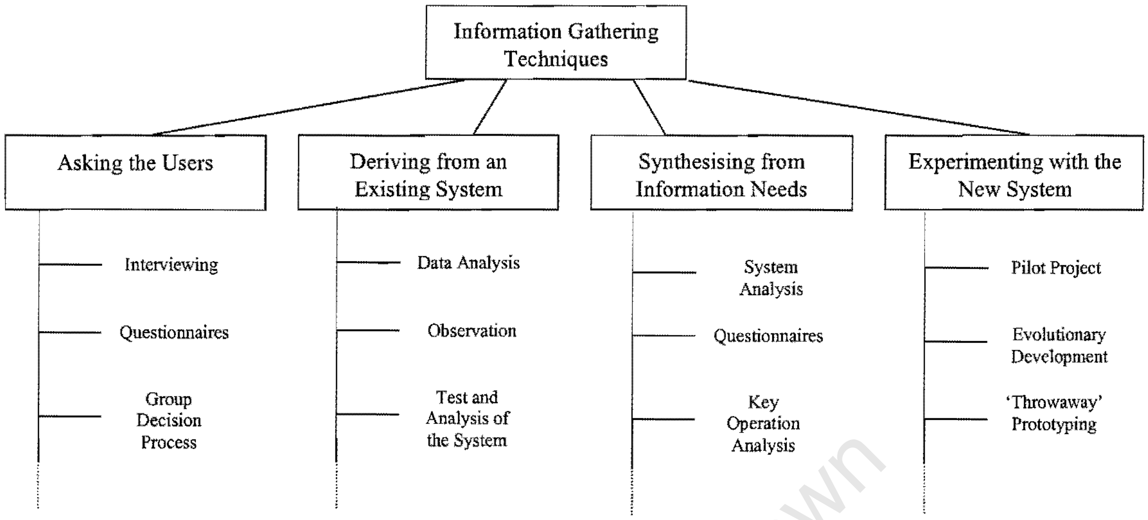


Figure 18 **Information gathering techniques**

Asking future users what they expect is especially successful if the users have a fair understanding of their requirements. Questionnaires are an efficient way of asking as many users as possible at once. However, there are limitations, such as the clarification of questions and follow-ups, it can also be difficult to motivate the user to fill in the questionnaire. Appendix 13.2.3 shows a questionnaire developed to establish expectations, requirements, needs and communication between the software developer and the organisation.

If an IS already exists within the organisation, it should be analysed and the users should be observed when working with the system. Investigation into current data management within the organisation can be another reference as to how the ISIS can improve the existing situation.

Instead of using a fixed project plan a prototype approach could be employed, whereby the ISIS is designed through experimentation. A pilot version is developed which fulfils a number of preliminary requirements. The users are able to define their requirements in an 'as compared to' manner. It makes it very easy for the users to see and follow the development process and an early familiarisation with the system takes place. This approach is specifically successful if the users have not yet been exposed to information technology.

Generally a combination of the above mentioned techniques is employed to analyse the future user, organisational needs and the data specifications.

6.3.2.1 Definition of Users

The main reason that ISs fail is that the users of the systems are not involved in the design process, or equipped to use the technology they are presented with, and do not really know what the system should actually be used for.

The development of a successful ISIS is dependent upon a detailed setup of the design specifications. These can only be defined once the user and his objectives have been identified and clearly understood. In order to solve a specific task the user needs data, information, technical tools (such as hard- and software), expertise and a suitable organisational structure. Information is derived by using an application, which accesses, processes and presents the data. The expertise of the user has to be sufficient to operate the tools and understand the functionality of the system.

It has to be understood that the user requirements of the project plan and the questions asked in the situational analysis differ in that the latter determines the up-to date situation while the former tries to establish how to design the system to satisfy future needs.

The user requirements can be identified in a number of ways, such as workshops, surveys or reviews of documented experience (Bernhardsen 1999). A standard questionnaire can be used to compile homogenous information from varying sources, but care should be taken in selecting representative respondents. In general it is important to design the system for the hands-on person, thus it might be more useful to interview the person who will work with the system instead of the organisation's executives. For an example of a user questionnaire see appendix 13.2. The information collected is then combined into a structured and neutral evaluation. At this point the team or person developing the system has the opportunity to address the established needs and requirements. The ISIS developers need to be able assist the user in understanding what the system will be able to do. The realisation of the user's needs and the attraction of using the newest available technology must be balanced. Consideration should also be given to what can be realised in practise within an acceptable time frame in respect of data capture, the building of expertise, and the creation of any necessary new structures.

The challenge in the creation of an archaeological ISIS is that a number of different users with completely different technological and professional backgrounds must be able to use the system. Project managers, site managers, conservationists, archaeologists and physical anthropologists may want to access the ISIS, but will have completely different requirements of the system.

The following table (after Zack 1997) shows the definition of different users, the tasks they perform and the data they need for these tasks:

Tasks Performed	Specialist	Data Needed
perform background research		Bibliographic Database
access field notes		Project Archives
access images		Image Database
categorise artefacts		Archaeology Database
identify site activity	Archaeologist	Catalogue
draw plans		Geographic Display Software
deliver artefacts to conservator		
access project plan		
write project report		
create datasets		
order supplies and equipment		Supplier Catalogue
review previous reports		Project Archives
gather previous correspondence		Monitor Station Report
gather environmental monitoring data		Samples
gather previous sampling data	Conservationist	Analytical Report
gather previous analytical data		
prepare conservation assessment		
gather site management plan		
prepare proposal		
distribute conservation assessment		
locate previous studies		
research site history		Historic Archives
research materials		Project Archives
determine project objectives		Budget
research construction	Project Manager	Contact Lists
determine budget		Legal Status
determine timeframe		Organisations
identify specialists		
draw plans		
recommend policy		

Table 1 User definition after Zack (1997)

6.3.2.2 *Need Analysis*

The Need Analysis defines the information needs of and the interchange between various organisational units, and helps to assess how the ISIS could be applied to these identified needs.

In many cases, departments may comprise of a number of smaller sub-units such as divisions or offices, each with separate and distinct functionalities. The need analysis will identify the function of each unit, which data is important for the unit, which non-digital data can be used, and where the data is to be stored.

Department:	Conservation
Functional Unit:	Documentation
Mission:	control conservation documentation ensuring quality of documentation
Subunit:	Library organisation

Functions	Main Data used	Other Data used	Source
documentation	documents		library
storage	documents		departmental reports
	digital drawings		intranet
	ortho-imagery		CD's
	site photography		hardcopies
	maps		

Current Data Problems:

- number of different digital data formats
- establishing relationship between data
- too much unorganised data
- difficult to find relevant data with search functions available on the system

Future Needs:

- user friendly interface for computer search
- new policy for data formats

Figure 19 Example of an ISIS Need Sheet

Recording this information for all participating users is a critical step towards the final determination of the content of the database required. The need analysis defines the needs of project advisors, team leaders, and team members, and it lays the foundation for the procedures essential for the operation of the system, since it identifies the flow and interchange of specific data such as maps or drawings, as well as the general data flow in the organisation.

The ISIS Need analysis records information about problems or inefficiencies regarding the current use of information. Later, for the design of the database and processing functions of the system, these problems can be addressed and possibly corrected. It also establishes what the users would like to see from the new system and what "needs" have to be fulfilled to make it a real innovation for the organisation. Performance questionnaires, shown in appendix 13.2, are a very efficient way of determining these answers.

6.3.2.3 Data Specifications and Assessment

Since the cost of directly acquiring digital data and the conversion of existing data to digital form generally exceeds the cost of any other component of the system, it is important to verify that each data item is in fact essential. The determination of the data items needed in an IS must be more than a 'wish list'. It must involve a systematic study of the relevance of each data item for the potential user. This process must contain the rating of data within the overall functionality of the IS to ensure an efficient, dynamic and optimised system. The accumulation of vast amounts of data simply because they are available, must be avoided at all costs.

Data Acquisition

Every computer-based IS uses digital data. The required data has to be collected and, unless it is already in digital form, converted into digital format, in order to organise the data in the IS database. Organising data into a structure is not only crucial, but also one of the most difficult and tedious tasks in the development of an ISIS.

Experience shows that data collection and maintenance accounts for 60-80% of the total costs of an established IS (Bernhardsen, 1999). An ISIS can only be beneficial if the data can be accessed at any time and if the data is processed efficiently. The choice of data should relate directly to the user's needs. Data may have been acquired at an earlier stage and is required to be included in the database of the ISIS. Thus an inventory of existing data is essential. Objective criteria, such as relevance and accuracy, should determine the data input. The creation of classes of data, e.g. documents, maps and images, can support this process by establishing relationships between data in the so-called classification process. In cases where more than one hardware device is used to store data, a record has to be kept of which data is stored where. When using more than one software package, e.g. for searching documents and to display geographical data, the data inventory should address the issue of which links will be established between the data and the software packages. It may be necessary to search a document for keywords in one program and to display descriptive information from the same document on a 3D image. Consequently, two packages will need to be able to access the same document at once, but the document does not have to be stored at two different places.

The *Data Input Sheet* reflects the important details of the input data. Figure 20 shows such a sheet. In general, information about the data format, where the data can be found or who is holding the data, the date of acquisition, and data quality will be recorded.

Data - Description	Format	Class	Stored	Date	Quality	Relevance
Description footprint G1-25	paper/ not digital	doc	Library	1978	2	high
contour line file G1-25	ARCINFO g1-25.e00	contour	CD 11	August 1995	1	very high
DTM file G1-25	ASCII g1-25.xyz	dtm	CD11	Nov. 1995	1	high
Orthoimage G1-25	TIFF g1-25.tif	ortho	CD11	Dec. 1995	1	very high

Figure 20 Data Input Sheet (Example Laetoli)

Regardless of the source of digital information, no digital data acquisition is error-free. In an automated environment these 'acquisition–errors' will cause conflicts and will result in a lower quality and reliability. To ensure that the acquired data is compatible with the database and to establish a system of standardisation for the data being used in the database, the development of a *Data Standardisation Catalogue* is essential. It defines standards, such as definitions and references, data formats, spatial data transfer specification, and digital data quality levels. Policies for data security, data maintenance and access rights for different departments can also be included.

Quality and Quality Assurance

ISIS data input procedures are error-prone and time consuming. The data is often derived from a variety of different and incompatible sources, such as ortho-image maps, historical and contemporary maps, as well as site surveys. A wide range of differing thematic contents, scales and methods of projection has to be coherently organised, and the quality of all the data has to be assured.

"Cornerstones" of integrating quality assurance into the life cycle of an information system are (McCain et al. 1998):

- Completeness
  The data has to adhere to the database design and has to conform to a set standard, which is laid out in the quality assurance policy.

- Validity
  A range of attributes and values has to be established within which the data has to fall to be valid for the system

- Logical Consistency
  The level of interaction and interconnection between sets of data has to be defined to allow the changes of functionally related objects.

- Physical Consistency
  The correctness of the physical data, such as topographical correctness or geographic extent of a site can often be measured. The requirements and accuracy levels within which the data has to fall have to be assigned.

- Referential Integrity
  A measure for the associativity between different data sets has to be established. Predefined rules allow the system administrator and the users to follow references within the data set and modify them when necessary.

- Positional Accuracy

Since positional errors are often introduced to the database by the data input, a measure for the extent to which spatial object positions should match reality has to be established. A policy on random, systematic and/or cumulative errors should be formulated before data input occurs.

The introduction of a maximum margin of error allows the administrator to determine which data should be accepted or rejected. It might be possible to inspect some data visually and to detect systematic errors, such as co-ordinate shifts or misspelled text. Some GIS packages offer an automated quality routine, where the database is checked for adherence to the database design, attribute accuracy, logical consistency and referential integrity. This is usually done in conjunction with visual quality assurance.

Defining a policy to determine acceptable data is a very intensive segment of the overall policy development. Which errors are acceptable, how are different errors weighted, and what percentage of errors justifies a rejection of the data, are questions that require a certain amount of knowledge of the data model, the database design, the user needs and the application requirements to be answered. Strict rules for the criteria for acceptance have not only to be formulated, but also to be adhered to. For a minor attribute a 1% error may not be crucial, but if the attribute serves as base data for other data sets, the error might cascade through the database and jeopardise relationships between data.

In the past, the issues of quality were often ignored because of additional short-term costs related to the implementation of quality control. Due to the high development and maintenance costs of a database, it may seem understandable to avoid additional costs by neglecting quality control. But the potential cost of poor data analysis, application reviews, and data reconstruction caused by the lack of quality assurance far outweighs the initial cost of a well-designed and well-executed quality assurance plan (McCain et al, 1998).

6.3.3 Stage 3: Design Specification

The design specifications are established by the requirements defined in the situational analysis and the project plan. These specifications have to be detailed enough to become inputs for the programming stage that follows. The design process is usually composed of two parts: the conceptual (logical) design and the detailed (physical) design. The conceptual model provides a general overview of the ISIS, while the detailed design produces a complete specification of the software modules and the database design. During situational analysis and project planning the focus was on what the system will do, whilst in design specification the focus is on how the system will do it.

During the logical design process the results of questionnaires are interpreted and translated into a logical sequence of tasks. The results of the user input questionnaire, the needs questionnaire and the system questionnaire are combined into a provisional overview. This overview has to be flexible to changes since the feasibility study and the pilot project may highlight procedures that have to be added, altered or removed.

The system design team can now define how the system will satisfy the user requirements, represent the developed mission, combine needs and technological advances, as well as ensure that all tasks are processed successfully.

Some of the most important decisions in the design phase are:

- the hardware and software components
- the combination of programs/packages that will constitute the application and the modules that will link them
- the specifications of the individual modules
- the design of the database
- the design of the user interface

- the development of procedures for the use of the system

The hard- and software components are chosen not only to satisfy current tasks but also attempt to take into account future needs and growth. Depending on the functionality required by the application, various programs and packages may need to be used. These, sometimes disparate, systems need to be linked together in a meaningful manner using program modules. The design of the database will be strongly influenced by the data to be stored and the methods of accessing it. Finally, the design of the user interface must be done in consultation with the users to ensure that expectations and ease of use are met. Documented procedures outlining how to use the application are crucial for the success of the system as well as assisting in the transfer of knowledge to future users.

Since the user interface is the means by which the user interacts with the system, an attractive graphical design that incorporates the many packages or programs in the background in a simple easy to understand manner is very important. At a later stage the specific graphical details of how the system 'looks' will be implemented, but at this stage of the design the display is less important than the functionality it represents. Appendix 13.5 shows a specific user interface in more detail.

Relational diagrams form both a visual and programming aid for the ISIS. These diagrams provide an overview of the data elements and the relationships between them. Applications will make use of one or more of these data sets to extract information. An example of a relationship diagram can be found in appendix 13.7.

During the conceptual design process, the controls as well as the security of the system are outlined. Once the conceptual design has been finalised, detailed design can begin. A set of all the system modules and the interfaces has been established and the database can now be created.

6.3.4 Stage 4: Design of a Database

The database is the heart of the ISIS. It consists of an organised collection of information represented by records. Each record is represented by a set of fields, which contains the individual elements of the information.

The data model of an ISIS describes entities and attributes, their relationship to one another, how they are used, and the processes used to manage them. Once defined, the logical data model is translated into a database structure that can be implemented on a computer.

Since an archaeological ISIS is defined by a set of data describing the real world, the data should be modelled as close to the real world as possible. The dynamics of the real world should be reflected in the database for it to remain useful in the decision making process. Since most users are not concerned with the internal functionality of the database, they should not be exposed to the low–level database mechanisms. GUIs allow the complex structure of the database to be hidden from the user whilst at the same time providing the functionality to access and view the data in a familiar windows environment. The interfaces should be self-explanatory and flexible, allowing both the novice user as well as the regular user easy access. Data needs to be retrieved as efficiently as possible and the user should be able to link pieces of information together.

There are a number of different approaches that can be followed when structuring data in a database, some of which are described briefly below:

The Hierarchical Approach

The hierarchical approach structures the data in a tree fashion, where each data item is linked to a group of subordinate items. This is a relatively simple approach, since there is only one path that can be followed down to a specific location in the lowest level of records. Figure 21 shows an example of data being organised in a hierarchical fashion.

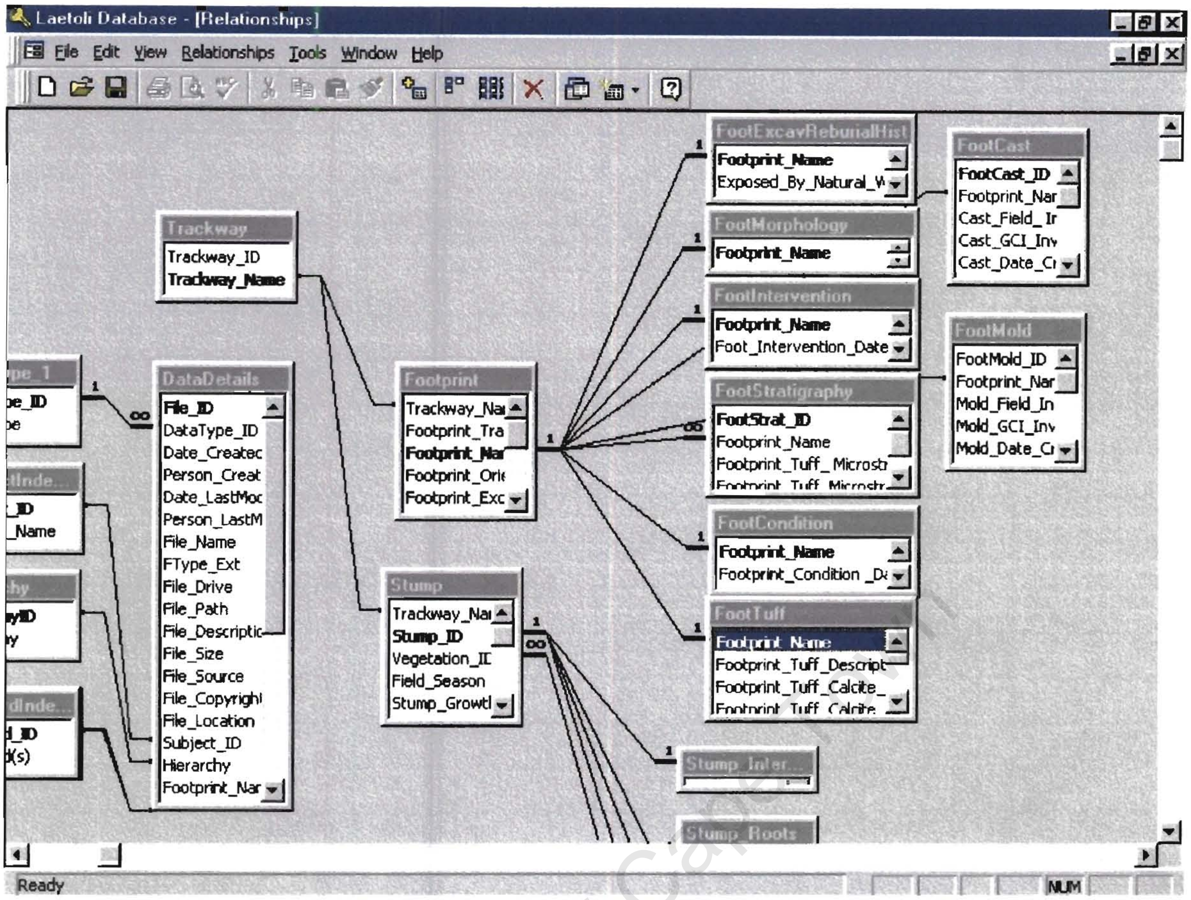


Figure 21 Hierarchical data structure

In the hierarchical approach the database is structured as one tree, and each individual tree becomes a sub-tree of the main tree.

The disadvantages of this approach are that it becomes cumbersome to traverse between data records and, since few real world situations are strictly hierarchical, the databases require replications of records or additional links, i.e. multiple tree structures.

The Network Approach

The network data model can be regarded as an extended form of the hierarchical data structure. The network model is more interconnected than the hierarchical structure since each record can have multiple links. A network of links connects the records and establishes relationships between them, i.e. the database consists of two sets, a set of records and a set of links.

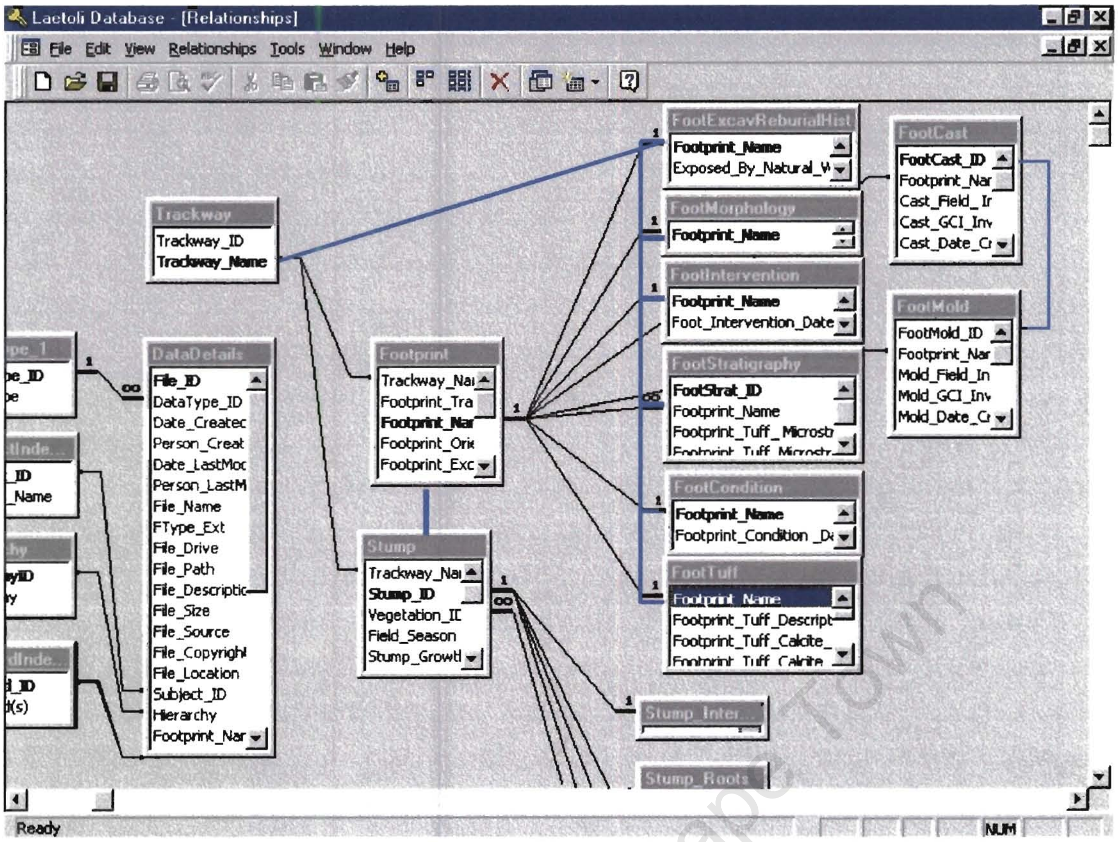


Figure 22 Network Approach

shows that the database contains the same information as the hierarchical database, but as indicated by the blue lines added connection can be established between data of the same level.

The hierarchical and network approaches lack flexibility because their access paths are pre-established through the tree structure and links created when the database is designed. An access point that is not provided when the database is designed cannot be accommodated without redesign.

The Relational Approach

A relational database is a data set that is perceived by its users as a collection of tables.

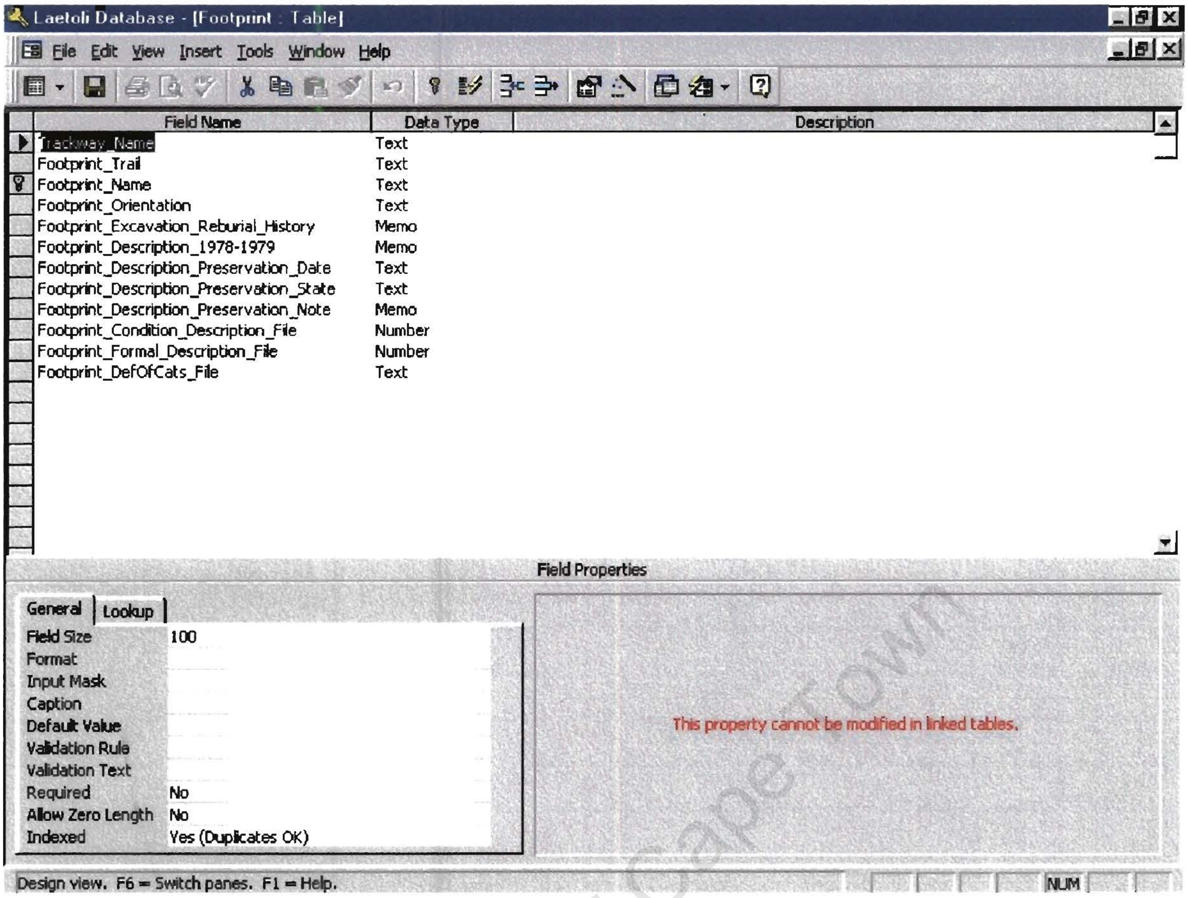


Figure 23 The Relational Approach

Figure 22 shows an example of the table 'Footprint' and its characteristics. Each field, i.e. Footprint Trail, Footprint Name and so on, contains the information for each footprint.

A relational database can consist of a number of tables. The relational approach establishes the relationships between the records without recourse to links, but rather through correspondence between fields. The data are represented in tables, where rows consist of a list of values for individual entities, while columns represent the fields of the records, which describe the attributes of the entities. It is probably the most popular database structure approach.

The disadvantage of this approach is that it becomes difficult to represent data that does not fit into the tables, such as images. The more complex the data, the harder is it to coerce the relationship into rows and columns, especially when performing reads and updates.

The Object-Oriented Approach

Object-oriented databases are able to store complex data structures, such as video, 3D graphics, compound documents or recursive data (Galphin, 1998). Storage and retrieval of the data is based on the concept of object-oriented programming, as realised in programming languages, such as C++ or Java. Instead of working with records, fields, and characters, the user thinks in terms of objects.

Object-oriented technology is defined by the following characteristics:

- Abstraction (Classes): A class is defined by the user and contains objects, which are associated with behaviours. Classes are arranged in a hierarchy.
- Inheritance: objects of lower level are able to inherit or access the data items of behaviours associated with objects of a higher level.
- Polymorphism: objects can be processed differently depending on their data type and class.
- Encapsulation: This refers to hiding data or behaviours, so that they cannot be accessed from the outside. This protects objects from being updated by an unauthorised source.
- Extensibility: New behaviours can be added to the objects

The primary benefits of object-orientation are that the code re-use is increased, thereby improving programmer productivity, and the system modules are managed via well-defined interfaces, which results in easier maintenance.

The above listed database approaches have various advantages and disadvantages. The best solution has to be established in accordance with the information system requirements.

6.3.5 Stage 5: The Combination Database

"The purpose of a database is to serve a user community as a data store for a particular range of applications." (Worboys, 1999)

The most appropriate database approach can be chosen according to the characteristics of the majority of required ISIS tasks. As seen for example in chapter 6.3.2.2 an information system should allow the project manager to retrieve data such as personnel data, budget data, samples or catalogues. This kind of data is usually best structured using a hierarchical approach (chapter 6.3.4). An archaeologist would require the ISIS to provide information about a specific site, such as condition reports, maps, or conservation methods, which would be managed efficiently by using a relational approach. Data like images and graphic displays can very easily be retrieved from object-oriented data models, since it is easy to define classes of different visual displays.

In an ISIS it might be difficult to establish which tasks have the highest priority and should therefore determine the database approach. The most feasible approach for an archaeological ISIS was found to be a combination of the database approaches listed in chapter 6.3.4. The combination database is realised by storing data within different models and using a network approach to connect these models.

The combination database approach has the advantage of being highly efficient in terms of data retrieval. This is accomplished by storing data according to its specification and using it in the appropriate context. As an example the Laetoli ISIS was required to display ortho-images overlaid with various condition reports (vector data). Textual information describing each individual report had to be displayed with each of these reports. It was necessary to allow the changing of the conditions report overlays consequently leading to an automatic change in the associated textual description.

The possible solutions for this requirement were:

1. The storage and retrieval of each possible permutation of the combination of ortho-image, condition report and associated text in a single format, e.g. as an image. This approach stores repeated information and is highly inflexible since the data can

neither be manipulated nor explored. It is not possible to create new scenarios and the database becomes excessively large.

2. The storage of ortho-image, condition report and associated text independently of each other. The data retrieval is done by creating a common link that imports the required data combination into a custom software application where it can be displayed, but not manipulated. This is a very common way of storing and retrieving data and is certainly more efficient than option 1. However, once the data is displayed, the individual files contributing to the display cannot be accessed. This means the user is able to interactively combine different data, but cannot edit it.

3. The data is stored as under option 2, but is retrieved in the associated software of each data format. This means the text would be displayed in a word processor, the condition reports in their original GIS package and the ortho-image as an individual backdrop image. The data is combined on the screen, but not within the individual data storage mechanisms. This allows the user with access rights to manipulate and interactively handle the data. In this option the data is still accessible when displayed.

Figure 24 shows the combination of an ArcView condition report, a footprint image (tif-file introduced as backdrop image), and the textual information in a Microsoft Word file. The overlays in the ArcView application can be changed for the footprint, and the associated text, which is displayed independently, will appear once the overlay is changed. Microsoft Access is used to manage the links and file path more than the actual data itself. The data can be stored anywhere, e.g. on a file server or even be retrieved from the Internet, as long as the path is referenced in Microsoft Access.

The disadvantage of the system lies with the inflexibility of pre-determined links. For the Laetoli ISIS this did not prove to be a problem and was offset by the quick data retrieval.

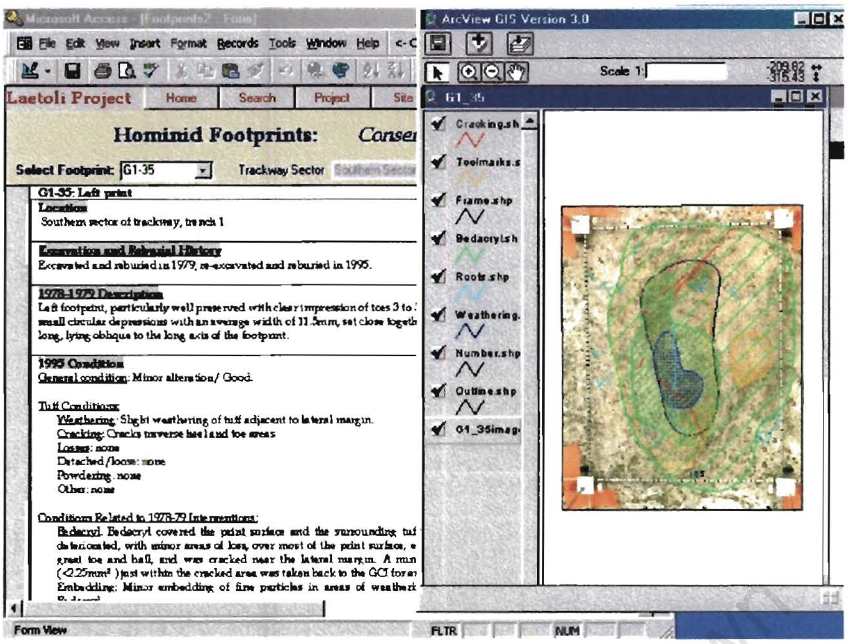


Figure 24 Combination of two software packages within one database setup (Rivett & Richards 2000)

The design requirements determined through the situational analysis, data requirements, need analysis, and the definition of the users must be translated into technical specifications that will be used to structure the database, select software, write custom programs and select and configure hardware. After structuring the database, establishing links, coding the necessary software a first feasibility study has to be done.

6.3.6 Stage 6: Feasibility Study

The feasibility study investigates the practicality of the ISIS. This section of the Strategic Plan aims to avoid the development of an ISIS that is impractical from the point of view of financial resources, technical compatibility, and institutional ethos.

Financial Feasibility

The purchase and implementation of an ISIS is an expensive decision for any organisation. Financial feasibility should be determined throughout the planning and implementation stages of the ISIS. This is accomplished by comparing the system's costs with the envisaged benefit, i.e. will the benefit outweigh the costs. Successful implementation requires a high level of commitment from both organisation management and users. Most organisations can only follow through with such a commitment if the expected payoff justifies the expense.

The cost-benefit analysis is the preferred method to justify the implementation of an ISIS, but it is only an adequate comparison if the organisation performs a separate cost-benefit analysis for the alternatives under consideration.

An initial cost-benefit analysis is refined during further stages of the development, but should always be within the predefined limits. A typical cost-benefit analysis contains several elements (Obermeyer, 1999):

- identification and assignment of a quantitative economic value for the implementation of the system
- identification of benefits, e.g. reduction of time and thus money spent on retrieval of data
- other areas such as cost reduction, cost avoidance and increased revenue play a major role in the IS development of the public sector or commercial organisations, but might have less impact in an archaeological environment.

Technical Feasibility

Of great significance are the criteria used to select the most appropriate technology. Basic support functions such as data query and display are far less complicated to implement than computerising certain aspects of the complex decision making process.

The technical feasibility study should therefore investigate:

- the level of complexity compared to competency and needs
- provision of different levels of technology to different users depending on needs

- guarantee of technical support

Institutional Feasibility

Institutional Feasibility deals with the willingness and ability of the organisation to accommodate change and new technology. The implementation of an ISIS can only be successful, if it is integrated into the philosophy of the organisation. The institutional feasibility study should therefore investigate, if the designed ISIS will be able to fulfil the following requirements:

- Can it be used for other projects?
- Does the system design fulfil the expectations of the user group?
- How integrated will the new system be within the organisation?

After investigating the financial, technical and institutional feasibility, original aspects in the design of the database or the ISIS might have to be adapted. This is to be done before the pilot project is performed.

6.3.7 Stage 7: Pilot Project and Implementation

The purpose of the pilot project is to examine the ISIS for feasibility, efficiency, and performance as well as to obtain user feedback. In contrast to the feasibility study the system is now tested by the future user, generally on a sample data set, to establish problems and to prepare the implementation of the system in the organisation. By pre-testing the system within the target environment a smooth hand-over during the implementation stage, that is when the ISIS is the physically installed in the organisation, can be ensured.

The scope of the pilot project depends on the complexity of the system. It should always be kept within reasonable limits in terms of time, budget, and the volume of data (Bernhardsen 1999). The tests performed should include the functionality, data transfer, applications, queries and test of required products, data access, security and the performance of the system. The results of the pilot project are assessed and evaluated before any further steps are taken, since at this stage the project can still be abandoned or changed completely, if necessary.

An ISIS is developed for its users and with the vision of being flexible and adaptable to changing needs. The design of the system is a complex process and not all users or maintenance personnel will understand all parts of the system. Because of this, one of the main tasks during the design stage is the detailed documentation of the system. During the pilot project this documentation is tested. At this point the project team is in a good position to confirm that all functions and the overall ISIS architecture is sufficiently recorded and explained.

Before an ISIS is implemented a detailed layout of the following aspects should be finalised:

- Data Compilation and Conversion
- Technology Selection
- Technology Installation and Testing
- Database Loading
- Software Customisation
- System Testing
- Demonstrations and Presentations
- Products

Addressing the above mentioned issues will help to create an overview for all participants, so that everybody involved will be able to accept the design before the actual implementation.

The introduction of information technology in the archaeological environment is not entirely unproblematic. All information technology falls short of its goal, if the users of the system are not sufficiently psychologically and technologically prepared. The obstacles that are encountered have their origins in such critical areas as ideology, price considerations, techno-phobia, and basic ignorance of the fundamentals of information systems as described by Sinclair (1992).

Users may remain apprehensive towards computers and it is difficult to overcome the psychological block this causes. The implementation of an ISIS in an archaeological organisation will introduce new methods of research, documentation, and even basic tasks such as searching for documents. Instead of looking through a physical folder, the user searches a virtual folder, which requires getting used to reading from a computer screen. Scientists may develop individual patterns for processing research, for example archaeologists who might be used to analyse data from paper sheets and may be loath to use the computer.

Another area that is affected by the introduction of an ISIS is the recording of archaeological data. As Sinclair (1992) describes it, archaeologists 'collect' data while excavating, sometimes without a direct analysis in mind, but with the hope that future research might find a use for it. In this case, the data collection itself does not present the challenge, but the way the data is introduced into the system. A number of policies have to be established to standardise the input of data collected in that manner. Before the ISIS, the documentation material, such as photographs or artefacts, are typically taken into a library and stored there for future use. Now descriptive information about stored artefacts, scanned imagery or documents have to be linked to the new system. Often the input forces the archaeologist to use a specific format to ensure the standardisation and quality of the data. Data that is collected without fulfilling the requirements of the ISIS will be excluded.

Established processes, such as documentation or research, which have developed over the years are challenged because certain tasks are now managed completely by the ISIS.

Investing more funds and buying better equipment and software does not solve the problem of getting used to a computerised working environment. The apprehension can be overcome by designing and implementing a flexible system according to situation, users and tasks required, which can be easily maintained.

6.3.8 Operation and Maintenance

When the ISIS is implemented in the organisation, it will operate like a production facility, processing data and producing information. Designed as a flexible system, representing the real world, it will need to be maintained to stay as successful as it is at the first implementation. Maintenance may include the correction of errors that were not detected in the testing phases or developed due to unforeseen events, such as hard- or software overload. Due to a constantly changing environment the request for change will be ongoing, either initiated by the users of the system or the management of the organisation.

The ISIS hardware has to be maintained to keep the system in working order without changing the software itself. Repairs, hardware updates, installation of added hard drives etc., is either done by the organisation itself or by taking out a maintenance contract with the hardware supplier. The cost of the maintenance is then very much dependant on the cost of the contract.

System changes are only possible if the ISIS software is easily understood, so that the appropriate components can be changed and tested after the system is updated. It might not always be possible for the development team to maintain the system, indeed it is rarely the case. Therefore the ISIS itself, or the documentation of the system design, has to be in a format that is easily understood by the person in charge of the maintenance, especially since one of the primary objectives of ISIS development should always be to create an easy-to-maintain system. Lehmann et al. (1985) stresses that a system is maintained over time and thus structures become more and more complex. In order to avoid the deterioration of the ISIS an active effort is necessary. A number of organisations choose to employ software maintainers, since this is cheaper in the long run than loosing the whole system from lack of maintenance.

Data maintenance keeps the database up to date. Depending on the layout and the design of the ISIS, update intervals have to be chosen. It is very important to ensure a regular data update, and it might even be of advantage to delegate this task to one of the users.

In an archaeological context, the operation and maintenance of a newly developed ISIS is perhaps even more important than in a technologically advanced environment. As described earlier, problems with the ISIS such as user apprehension, are worsened if the data retrieval is slow or if the data used is out of date. Since this can mean the failure of the whole project, maintenance has to be a structured process that is supported by the project management team.

6.4 Summary

The objective of chapter 6 was to develop a pragmatic and dynamic model for the management of the spatial data acquired in Chapter 5 and its support or meta data. The design of a specialised database, which is able to cope with the combination of spatial, descriptive and visual data, was required.

After defining the terms Information System and Management, and determining the difference between a GIS and an ISIS, the objectives of an ISIS design were established.

Some of the key issues mentioned were flexibility, dynamic representation of archaeological methods and concepts and the possibility of data representation. The important finding that there is no off-the-shelf solution for such a highly specialised system led to the next step, the design of an archaeological ISIS.

A strategic plan was developed, showing a step-by-step model. With the help of a situational analysis, a project plan, detailed design specifications, a pilot project and a well-planned implementation, operation and maintenance process, the method for the design of a successful ISIS was presented.

The situational analysis seeks to understand the current scenario into which the ISIS will be implemented, thus allowing a representative design. This 'philosophical' definition of the

ISIS determines how the user, the management team and the organisation will identify with an ISIS and how and by whom it will be supported. The psychological impact on the working environment due to an implementation should not be underestimated, and the success or failure of the ISIS will be dependent on the mental preparation of the organisation for the expected changes.

With the project plan a more detailed layout of what the system will need to handle is identified. This process includes the specification of the user, the analysis of needs, and the data specification.

The design specifications can then be created, whereby important decisions, such as hard- and software components, design of the database, the design of the user interface and the procedures for the system will be made.

One of the key issues in the design of an ISIS is the selection of a database model that best satisfies the system requirements. The approach offered is a combination database, which manages data by combining approaches and software, according to the data formats. The effective storage and the fast data retrieval create a stable database and retrieval subsystem for the ISIS.

The feasibility study should confirm the decisions made, reject parts which will not be supported and otherwise give the go-ahead for the ISIS creation by testing the financial, technical and institutional aspects of the ISIS design.

The pilot project ensures that all requirements are fulfilled and the user will have at this stage the possibility to familiarise himself with the system and identify missing features. Implementation, Operation and Maintenance plans have to be established at this stage, which lead then to the successful use of the system.

In conclusion, it can be said that the method presented for the design of an ISIS offers a solution to the problem of creating an integrated system that is economically feasible and flexible enough to allow software, hardware and data up-dates at any stage. This is especially relevant in the light of rapid technological advances that can make a system redundant if it is unable to cater for these new developments. Using a database model that allows for fast updates and variations in data input also enhances the flexibility of the system. The combination approach, which was introduced in this chapter, has proven to be successful by increasing flexibility, speed, and performance of data retrieval. Storage space and system crashes were minimised.

There are arguably various alternatives to design an ISIS and similarly a number of different approaches could have been followed. IS technology is developing rapidly, and is moving towards open information systems and neural network approaches, which will create a new range of possibilities. Most of the alternative approaches investigated were rejected due to financial constraints. The ISIS was designed for a specific project and organisation, and one of the main requirements was to create an information system using commercially available software.

7 Data Representation

Up to this stage of the ISIS development the discussion has covered how to acquire, manage and retrieve data. However, the real success of information technology and its great potential are strongly connected to the new possibilities of data visualisation.

Data collected on an archaeological site can be represented in a number of ways, such as descriptive documents, maps, photographs and drawings. The technological development of computer graphics have added a variety of new possibilities, for example, 3D visualisations, virtual reality models and computer aided drawings.

Visual reconstruction of buildings and artefacts on the computer screen have become more and more popular (Palamidese 1993), since they not only represent a visual impression of the object, but have become a very useful aid for understanding and researching objects.

The following chapter introduces the visual representation of spatial data in the context of spatial information systems. It presents an overview of the possibilities and approaches of general and scientific visualisations (chapters 7.1 and 7.2).

The integration of visualisation tools within an ISIS is still a challenge and will be discussed in depth from Chapter 7.3 onwards. A method on how to approach the tool development is suggested, with explanations on the definition of tasks, choice of approaches and programming languages, the implementation of users and their interactions, as well as the graphical design of the tool itself.

The flowchart below gives an overview of the chapter, by showing the development stages for the visualisation tool using the data acquired by means of photogrammetry and managed by means of ISIS.

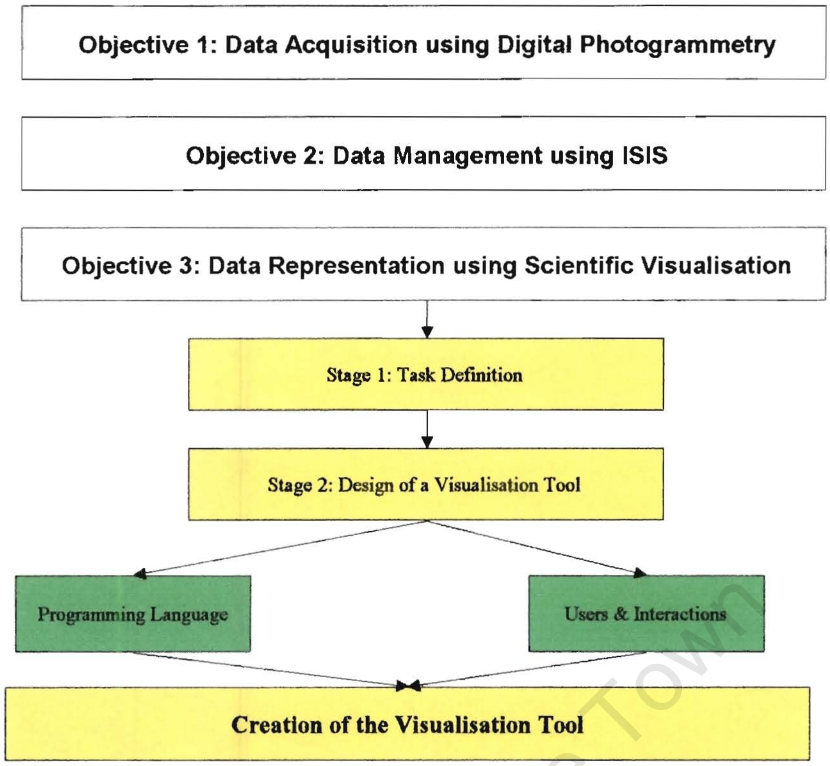


Figure 25 Chapter Overview

7.1 The Visual Representation of 3D Data

The purpose of computer visualisation is to create a visual model of reality. To model reality as clearly as possible, it should be as close as possible to the human experience.

When attempting to analyse or model physical processes or data, it can be very difficult to describe them. This is due to the inherent complexity in these processes, as well as inappropriate, inaccurate or missing data. To provide insight into the complex and subtle relationship within data, exploratory data analysis can be a very useful tool (Gahegan, n.d.). Digital visualisation offers a means to explore data by combining, displaying and analysing several data sets concurrently.

Van Driel (1989) recognised that the advantage of 3D displays lies in the way the information is perceived. It is estimated that 50 percent of the brain neurones are involved in vision. It is also believed that 3D display stimulates more neurones, thus involving a larger portion of the brain in the problem solving process. 3D displays simulate reality and allow the viewer to recognise and understand the object quickly. This leads to a higher analysis potential.

In contrast to image processing it is not the aim of computer visualisation to recognise and extract structures in data, but rather to present the data to the user in such a way that the task of interpretation is made easier. Possible aims of visual analysis are

- to search for trends in the data
- to examine the variation of one data set in relation to another
- to combine several data sets.

It can be argued that the human visual system has not yet been challenged in the field of image interpretation. Therefore the human should be involved in the exploration and interpretation of the data and the visualisation tool should facilitate this.

To create a natural 3D scene on a 2D-computer monitor some visual cues are necessary. By using aids such as perspective rules or the subtle change of colour and texture with respect to change of distance from the object, a realistic impression can be created.

The minimum data required for the creation of a 3D scene are points with 3D co-ordinates. These can either be organised in the format of a DTM or DEM (chapter 5.5.2 and appendix 13.1.5), a regular grid or a point cloud. Ortho-images can be used to enhance the realistic impression of the object by draping them over the surface created by the DTM/DEM.

A number of commercially available packages offer '3D visualisations' and most GIS packages are able to handle DTMs and integrate tools for '3D visualisation' of data. Dimensionality in digital models has to be defined carefully. It has to be distinguished between 2D, 2.5D and 3D models.

2D models are usually defined by two co-ordinates, e.g. x, y, and an attribute, e.g. tree. 2.5D models introduce the height as an attribute, e.g. x, y, z(a). Although the z (height) co-ordinate is available as an attribute, each x, y point can generally only be assigned one z co-ordinate (Kraus, 1997).

3D models are represented by a system of volumes (Scott, n.d.) and are described by three co-ordinates and an attribute, e.g. x, y, z, a. Where a set of adjacent surface models is brought together in one co-ordinate system to describe for example a tower to its full extent, more than one z value can exist for each x and y co-ordinates which, according to Kraus, is the definition of a real 3D representation (Kraus 1997).

GIS software can generally deal with 2.5D data. Although one might assume that in the commercial sector of GIS and spatial information systems, that there would be software catering for 3D data visualisation. This is not the case for currently available commercial GIS packages. Only a limited number of functions are under the control of the user, which create a 3D impression by using colour coding or shadows.

By using the approaches developed in scientific visualisation, an information system can be extended to include a full 3D display.

7.2 Visualisation in Scientific Computing

Human cognition is essentially spatial with objects being made 'visible' in the mind. This creative process of human visualisation can also be used if something is not visual at that moment in time. Humans can 'remember' what an object looks like, or can imagine what it should look like. However, different individuals have different methods of visualising. Depending on background, education, and environment the imaginary visualisation of the same object may vary between persons. Sometimes it will not be possible to imagine something, because there is no experience associated with the data, or it is too complex to be visualised. If one would ask an archaeologist, a layperson and a mathematician to imagine 3.5 million years old footprints in volcanic ash, one would find that all of them would have a personal perception of what such a footprint looks like. Certain aspects might be the same others will differ. The added information of 3.5 million years might change the perception of some, while others might not be able to imagine how the 3.5 million years would affect the imprint. The number is too abstract to create an image from it. Thus it would be obvious to show a photograph of the footprints to create a common impression, since the perceptions differ too much to serve as a common image.

In the last decade the term visualisation has taken on different meanings. Up to then it was generally defined as a mental process, which creates a visual representation of something, which is physically not available. With the development of computer technology visualisation became a synonym for exploring data in visual form on a computer screen (Visvalingam 1994). The capacity to generate and interact with realistic images and the tools provided due to technology have been exploited in the fields of science and research.

Visualisation in Scientific Computing (ViSC) is the discipline concerned with the development of tools, techniques and systems for computer assisted visualisation. "It studies those mechanisms in humans and computers which allow them in concert to perceive, use and communicate visual information" (McCormick et. al 1987).

Wood et al (1994) defines the term as a "set of tools (today, mainly software) used to permit visual data analysis. Thus, through images displayed on computer screens, assistance is provided to human information processing, enhancing mental visualisation and the comprehension of 2D and 3D spatial relationship and spatial problems". The tools Wood describes offer more than just a display, they include animation (flythrough and 3D visualisation) and interaction with the data.

ViSC is based on the process of creative thinking and translates data into a visual representation on a computer screen, by creating a complex set of rendered images from raw data (Haber et al.1990).

Due to the dynamic facility of interactive access and manipulation of data it is believed to offer a "brainstorming environment, which reveals anomalies or unexpected trends and patterns" (Brodlie et al. 1992).

ViSC should be seen as the philosophy behind visualisation-tool-development. It is in itself not a programming language or a design layout, but describes the expectations of the user based on his mental process, experiences of previous software or the general environment.

An archaeological visualisation tool, which is used to experience and analyse data that is physically not available, should be designed according to the philosophy and methods of ViSC.

7.3 Design of an Archaeological Visualisation Tool for an ISIS

Archaeologists have extensive spatial data handling requirements (Lock 1992). Archaeological phenomena are defined by their unique position in space and time, and by the latent relationship existing between them. Traditionally, archaeologists used maps to visualise spatial information. Vast quantities of locational and thematic information can be stored on a single map and yet, because the eye is a very effective image processor, visual analysis and information retrieval can be rapid for the trained person. Therefore it is not surprising that maps have formed the basis for visualising spatial data from early historic times (Fletcher 1992). With the development of the Internet computers have become a communication media, and with the policy of sharing data world wide, computer graphics and image processing are playing an increasingly important role in archaeological research (Sinclair 1992).

The challenges of creating a visualisation tool can be broken into two independent issues.

The one is the overall complexity and volume of the data. There is often more data available than can be simultaneously visualised even in the most advanced environments. This makes it necessary to select some data and reject other.

The other issue is the assignment of the data to the parameters that control the visualisation, as determined by the chosen environment. Without a structured and controlled approach the possible visualisations could soon become prohibitively large (Gahegan, n.d.).

The production of the visualisation tools requires an awareness of issues concerning data reduction, generalisation and the assignment of data to visual parameters. Additionally, different types of constraints must be applied concerning data properties and the facilities provided by the visualisation tool environment.
Visualisation tool design may be undertaken as a formal procedure. The user interaction-model of the ISIS can be implemented and through a cognitive task analysis the phenomena that need to be displayed are defined. The tool designer determines how the phenomena are displayed to reach the communication objective, which is determined by the user community.

The design of the visualisation tool comprises the following steps:

- Definition of the tasks the visualisation tool has to fulfil
- Definition of phenomena that need to be displayed
- Definition of the display graphics
- Choice of the visualisation system
- Choice of the programming language

Before describing these tasks in detail a few words must be said regarding the integration of a visualisation tool within an ISIS. The design of the visualisation tool is a critical aspect of an ISIS, especially when the images are to be employed for spatial decision support (Wood et al.1994).

Integrating visualisations or any kind of multimedia within a spatial IS system is a relatively new concept. Up to now there have been two strategies to combine the visualisation tool and the IS. One of them was the 'GIS in Multimedia' approach, whereby a proprietary multimedia authoring tool is used to integrate different data types and analytical functions. The other one is the 'Multimedia in GIS' approach whereby the multimedia handling capabilities of existing GIS software were increased (Moreno-Sanchez 1997).

A new approach is presented in this thesis, which uses the advantages of an ISIS to manage the volume of spatial data and displays data in a linked, but independent, visualisation tool. This could be described as 'IS and Multimedia' approach. The difference between the 'GIS in Multimedia' approach and the 'IS and Multimedia' is, that the latter does not employ a multimedia software for data storage, rather keeps the two applications separate. With an independent visualisation tool, the full potential of a scientific visualisation approach can be realised. The two systems are connected via an interface, allowing the user to switch between them, without being exposed to the processes running in the background. Different information can be displayed at the same time on one screen. One of the major advantages of this approach is that the data mass is organised efficiently and consequently system overload is less likely to occur.

Before starting to design the tool and creating the connection between the visualisation and the database of the ISIS, a few issues have to be considered:

- One of the major issues for any visualisation design is that the development depends on technology, which changes at a rapid pace. These dynamic changes can lead to a situation, where the development is technology-driven, rather than satisfying the users needs. It can be argued that, despite not using the newest technology, an integrated visualisation tool can be successful if it is addressed to meet the needs of the end user (Moreno-Sanchez, 1997).

- Another issue is the concept of 'perceived usefulness' and 'perceived ease of use'. Perceived usefulness is the degree to which a user believes that a system would enhance his performance, while perceived Ease Of Use (EOU) is the degree to which a user would identify a system as easy to use (Davis 1989). These two factors affect the whole system, not only the visualisation tool. While users might find a system easy to handle, they might not be convinced of its usefulness. A system becomes a toy, if the EOU is high and the usefulness is low. The opposite, low EOU and high usefulness make it a power tool, but a novice user might not be able to see a benefit in the system. The goal has to be to create a 'super tool', which combines a high level of EOU and usefulness (Keil et al. 1995).

- To establish a convincing EOU, the user should be supported by providing comprehensive error messages, on-line help facilities, compliance with international standards, and customisation when suggested.

- The visualisation tool should be as flexible and dynamic as the ISIS. During the development stages it should be ensured, that future software updates are easy to handle, and future developments can be integrated.

- The visualisation tool and the ISIS itself must adhere to the same data and quality standards.

These issues have to be addressed throughout the design of the visualisation tool and are also addressed within the design of the ISIS.

Before choosing a suitable programming language, the tasks required of the visualisation tool must be defined.

7.3.1 Stage 1: The Task Definition

The task definition describes the objectives of the visualisation tool and the actual functions it must perform. Visualisation tools are usually designed for specific applications and thus the objectives are formulated for each individual system. In the context of archaeological ISIS, some of the fundamental objectives of a visualisation tool are common, such as mentioned by Abouaf (1999):

1. Convenience and Interaction

   Viewing artefacts on a computer screen allows the user to see the object in a realistic resolution. The data can be presented as an interactive experience, as a self-directed tour from different perspectives, or as individual selected parts. Modules such as 'what if' scenarios, exploratory graphics and ready-to-use functionality allowing easy access and manipulation, should be some of the basic functions provided.

2. Precision

   During the data acquisition, the exact dimensions and proportions of the artefact or site were established. The accuracy of the 3D visualisation is the direct representation of data acquisition accuracy. This means that the 3D visualisation cannot improve the data, it just allows a different view of the data.

3. Problem solving

   By exploring the data visually and by providing various perspectives of the same data set the analytical research of an object can be increased. So can, for example, the walk of the hominids in Laetoli be re-created and various possible scenarios of the events 3.5 million years ago be analysed.

4. Communication and Data Distribution

   The tool may be distributed via the Internet, customised versions can be shown in museums and the overall documentation of a site is no longer connected to files and documents stored in one place. The experience of data exploration can be shared, site visits are possible for everybody and not only to a selected few.

5. Stimulation of new research

   Different representations of the same data or of a process enable a user to focus on different aspects of the problem. The visualisation tool should be created to stimulate future research by implementing various exploration tools.

These five objectives outline the philosophy of the tool development. Practical considerations should comprise of low hardware requirements, easy-to-learn outline, interface customisation, national and international interface standards (e.g. Microsoft Windows®).

The software programs that are often adopted by archaeologists to reveal relationships within an archaeological 'reconstruction' are not specifically designed for this purpose. They address a wide audience of clients and are intended to work equally well irrespective of whether the output is a new car design, an atomic structure or a building and will therefore compromise on certain aspects, such as accuracy or functionality. Moreover, when archaeological data is the source, modelling will usually entail a high proportion of subjective judgement, since many parameters may not be known. Computer visualisation software allows parts to be re-placed, copied and edited, to 'perfect' the model – which may detract from the actual object. Computer generated models of archaeological artefacts which give a 'star wars' impression might be found more confusing than an actual aid for further academic research. It has to be the objective of all scientific visualisation to show the object as realistically as possible to utilise the human abilities of observation and perception and to combine it with the experience and intuition of archaeological knowledge. The combination of visualisation and experience is yet another very important characteristic of the visualisation of archaeological objects. The interaction between the archaeologists and the computer is a vital element to the investigation and research process. Functions such as views from different angles and distances, a variety of lighting conditions, colour changes as well as measurement tools should be made available and controllable by the archaeologist.

An analysis of requirements and expectations should be performed before the design takes place, which should investigate questions such as a detailed definition of the tasks, the various user groups and their requirements, performance and functionality expectations.

Some of these tasks have been described within the layout of the ISIS and for these the stage of task definition may only be a matter of describing the display of the phenomena. Phenomena are classified by different graphic displays, such as exploratory graphics, design graphics and reference graphics. In the class of exploratory graphics, information generated from numerical simulations or other modelling is displayed. The design graphics allow the user to design solutions by modifying data. The reference graphics display data that contain either textual information to explain the display or links to other sources of documentational information such as Web Pages. How many and which combinations of the graphic displays are introduced is dependent on the design of the ISIS, the data and the design of the visualisation tool (chapter 10).

For traditional tool development, it is often assumed that the requirements and specifications can be completely defined during the analysis phase. This is generally not the case for the design of a specialised and integrated visualisation tools. The user may not fully understand or be able to articulate requirements early in the development cycle

(Moreno-Sanchez 1997) or may just not be aware of what the system is able to perform. Sometimes it might be a better approach to establish the task the user would like to see by experiencing it. By developing concentrated modules and prototypes the user learns to use the tool and can comment on its performance, which allows a mutual understanding between the designer and the user. This learning experience should take place continuously during the development (Chaudry et al 1995).

In an archaeological environment some of the fundamental tasks of the ISIS integrated visualisation tool include:

- Measurement tools (e.g. distance measurement between user defined points)
- Height exaggeration, flood- or cut-planes, profiles and gradients
- Viewpoint and movement tools (projections, light, colour)
- Appearance (texture overlay, transparency, solid and wireframe models)
- Fly-throughs and various zooming functions
- Simultaneous display of image and textual information
- Querying several layers of information
- Production of customised outputs, such as maps and tables

These functions and tasks have to be translated into a visualisation tool, with an appropriate programming language to allow the linking between the data and its visual representation.

7.3.2 Stage 2: Design of a Visualisation Tool

With the design of the ISIS, the relationships between data have been established, needs and tasks have been defined and a clear structure has been developed. The visualisation of the data has to compliment that design, and needs to be implemented within the ISIS in a way that does not interfere with other data or slow the processing speed down. The choice of the visualisation content and the layout may be considered in terms of the relationship between data, the range of possible communication objectives and the relevant context. The aim is to communicate specific information about a data set by using a realistic visualisation, which incorporates recognisable properties of objects and scenes appropriate to the user's existing mental model.

The designer of the system has to make the decision of which phenomena need to be displayed and what kind of representation is chosen. Turk (1995) describes a model where the tool is designed according to increasing levels of automation.

Level 1: Informal visualisation, where the design is based on the intuitive behaviour of the user.

Level 2: Theory based visualisation, where the design is based on an integrated set of explicit theories from the relevant disciplines, rendered coherent and tractable through an integrated theoretical model, but not operationalised as principles or procedures.

Level 3: Principles/procedure based visualisation, whereby the application is defined as a set of principles and rules, formal models and design procedures.

Level 4: Automated visualisation design, which uses knowledge based system software implementing formal (computational) analysis and design models.

Since the scientific visualisation tool is primarily developed to help the scientist to extract ideas and solutions from a vast amount of multidimensional data it has to be designed to fulfil his needs. It can be assumed that the scientist who is supported by the system is not necessarily a specialist in ViSC. Thus the designer of the system should establish what kind of a user he is dealing with and what kind of interaction this user will require.

7.3.2.1 Users and Interaction

For the design of a visualisation tool the intuitive knowledge of the human has to be translated into functions, which allow the user to behave the same way in the virtual world as he would behave in the real world.

The human visual system is based on experiences stored as knowledge in the brain, which identifies an object and recognises it. With this knowledge, the human can identify an apple and knows, that it is for example difficult to determine the colour of an apple in a tree when it is seen against sunlight, and thus he will move his point of view so that the sunlight is behind him (Hearnshaw 1995).

The knowledge that a difference in form between two objects is easier to distinguish than a difference in size, that contrast enhances detection, that illumination, within upper and lower limits, improves detection, and that regular, simple geometric forms are easier to identify than unfamiliar, asymmetric ones, can be applied to improve the user's perception of displays.

Users are the most variable component of the system. They vary in a number of ways, such as their ability to understand the conventions of the human-computer interaction. The way they interact with the system and the format they would prefer for the information display will differ from user to user. Some users will only want to see the functions they need, while others want to discover all the details. Users also differ in their cognitive, perceptual and psychomotor skills, i.e. their problem solving and pattern recognition capabilities. Even if the visualisation tool should cater for a wide audience, it must still address individual needs, work culture and practices. The last and probably most difficult feature of the user is his expectation. Comparing the tool to previous experienced software, the hope to find a 'tool that solves all problems' or the fear that this tool will be 'a waste of time' will have to be addressed.

A visualisation tool can be described according to the following four aspects, which will allow the tool developer to layout a model design:

1. Purpose of the Visualisation – Some of the visualisation packages offer additional possibilities for extending visualisation towards realism. While the idea of walking or flying through a simulated landscape is clearly attractive to many users, it has to be established if it is of any benefit to take a virtual stroll through an abstract 3D scene.

2. Degree of Interactivity – The scientist interested in posing ' what if?' scenarios will generally demand an interactive capability. Interactivity depends on hard- and software developments in the IS environment. Highly efficient data storage and data extraction systems have to be designed to interactively explore the IS data sets using the graphical models.

3. Degree of Abstraction – Abstract representation may be largely unfamiliar to someone not trained in visualisation tool use, while less abstract representation can provide a view both familiar and accessible to the general public. For the non-scientific audience abstraction should be minimised, and the information content maximised. The whole visualisation tool must be user-friendly and non-threatening. Those not trained in interpretation of abstract information should be able to work with the tool on an intuitive level.

4. Aspect of phenomena – The data representation has to be in line with the phenomena for which it provides a model. Complementary to this is how does the graphical displays represent the data. Issues such as the use of symbols and classifications have to be addressed. The result should be a display that becomes self-explainatory in the context of the project.

The user has to have control over the visualisation tool. Using Graphic User Interfaces (GUI's) control functions can be introduced in a windows format which are self-explanatory and generally familiar to the user due to developments such as Microsoft Windows®. Components of the interface can be made to look like control familiar to the user in the real world (e.g. stop signs). The use of these metaphors can be effective, if they are designed appropriately.

The user should also be able to interactively change properties, such as viewing parameters. This allows the user to filter quickly through many instances of representation and creates the feeling of being in control of the system.

Fast visual feedback is another desirable element. Delays are annoying, especially if they interrupt the work flow or distract form the current line of thought. Variations in response times are often felt to be even more annoying than consistently long responses (Medyckyj-Scott 1995). If long response times cannot be avoided, some feedback, in form of progress indicators, such as hour glasses and progress bars, should be used.

One of the great challenges when designing a visualisation tool is the fact that each computer screen has a limited size. Thus it is almost impossible to display all the information the user wishes to see at the same time. Window design becomes a key issue for the design of a visualisation tool. Optimal use of screen space can be rather difficult, and should be investigated thoroughly. The user often expects to be able to display the same data set from a number of views and to see these different events simultaneously on the screen to compare and differentiate between the various representations and to better understand the data. However, even if multiple windows increase the perceived viewing space, they may not necessarily increase the visual scope of the user. Poorly designed interfaces can result in difficulties such as information overload, confusion, disorientation, and distraction. The user must be able to rearrange the screen to present the data in a convenient way. A number of strategies have been developed for the cognitive processing strategies for screen design (Norman et al 1986). Experience shows though, that outlines tested by the user during the development phase are still the most successful way of determining the acceptance of the tool.

During the design analysis of the visualisation tool a decision has to be made as to which programming language or software should be used to create the tool and establish the links to the database of the ISIS.

7.3.2.2 Choosing a Programming Language

The purpose of this chapter is to introduce the basic concepts of 3D graphics programming, but it does not intend to describe the technical details of languages or programming code.

Visual programming languages use graphical and pictorial objects to represent the programming constructs typically found in traditional programming languages. These constructs include data types, such as variables and arrays, as well as functions and operators. Some representative visual languages will be introduced in the following section. Presented are only the ones, which were used to program the 3D visualisation tool for the Laetoli ISIS. Weaknesses and strengths, as well as the advantages of each language will be introduced briefly. One of the prerequisites of selecting a 3D visualisation programming language was that it had to run on popular operation systems and workstation platforms.

VRML

VRML stands for Virtual Reality Modelling Language and is the standard language for 3D graphics on the Internet. It is platform independent and takes the form of an ASCII file describing a 3D object. VRML runs within in a web browser as opposed to most other visualisation packages such as Java3D, which are standalone applications.

The VRML console provides the basic movement tools used to navigate through the scene and is designed to make use of existing standards of the Internet, such as JPG image format, WAV sound format, JavaScript scripting language (appendix14.1).

In order to make VRML feasible for 3D visualisation over the Internet certain inherent design restrictions are necessary (Taylor 2000):

- To decrease download times VRML files are restricted in size. Files must be efficient at describing the scene using as little code as possible (e.g. by avoiding unnecessary duplication of data).

- Plugins have to be downloaded, which interpret the code and run it on the browser. However, running VRML on the latest browser version (e.g. Netscape Communicator 4.5) does generally not require any plugins to view VRML files as they are already built into the browser.

- One of the key considerations for the success of a 3D visualisation tool on the Internet was the ability to share models on the Internet and include them as parts of any scene. Files and code of other work can be incorporated into VRML programs and this is a great asset of VRML.

VRML is designed to integrate well into the Internet. The limitation on file size and the need for plugins restrict the ability to have rich features that one would expect from a fully-fledged 3D package. The difficulty in performing specialised tasks and creating user interaction in VRML stems from the fact that the necessary modules or mathematical functions have to be programmed without the help of any basic mathematical libraries. Depending on the definition of the visualisation tool a compromise has to be found between the ease of sharing VRML files on the Internet and the difficulty to program certain functions. The difficulty of creating tools for user interaction is confirmed by the lack of interactivity found in most of the VRML files available on the Internet.

JAVA 3D

Like VRML, Java3D is used to create 3D scenes. It is a full-featured, high performance 3D graphics architecture that was established as an extension to the Java programming language. It is an application program that yields a high degree of interactivity while preserving true platform independence and it provides a number of functions for the creation of imagery, visualisations, animations, and interactive 3D graphics (appendix 14.2).

A Java 3D program creates instances of Java 3D objects and places them into a scene graph data structure. This graph is an arrangement of 3D objects in a tree structure, which describes the scene and how it is rendered. It is a hierarchy of nodes and groups of nodes, which form the instances of Java3D classes. The nodes comprise data elements connected by arcs, which determine the relationship between the data. The data elements are organised in classes, which are objects in object-oriented programming languages. An example would be a class called shape, which contains the objects circle, rectangle and triangle (Rozendaal 2000). Within the class, properties of the objects are defined.

Interaction and animation is one of the major benefits of Java3D. By defining so called 'behaviour classes' a mechanism is defined which includes the code to change a scene. To allow the change to take place a stimulus has to be defined, which can be the pressing of a key, a mouse movement, the collision of objects, the passage of time, or any other event (Gundrum n.d.). The possibilities are only limited by the capabilities of the scene graph objects.

VRML and Java3D share common ideas in functions such as shapes, appearances, grouping, transformations and lighting. The concepts are similar, but there are also some major differences, such as:

- Java3D has more extensive support for geometry, texturing and transparency, viewing and rendering, transformations, lighting, sound playback and input devices

- Java3D offers more support for background, behaviour, and interpolation.

- VRML is a file format, while Java3D is an application program interface.

It is often stated that VRML is easier to use than Java3D, but the latter is far more powerful (www.sdsc.edu/~nadeau/talks/nasa_eosdis).

OpenGL

OpenGL stands for Open Graphic Libraries and is 'the most widely adopted graphics standard' (www.opengl.org/About/About.html). It is an environment for developing portable, interactive 2D and 3D graphics applications and offers a broad set of rendering, texture mapping, special effects, and other powerful visualisation functions. It was introduced in 1992 by Silicon Graphics Inc. and was one of the earliest visualisation environments developed, thus serving as a standard for other visualisation developments.

It is independent of display hardware, operating system or platform. Some implementations of OpenGL are entirely software driven, while others use the specialised graphics available on some workstations, such as Silicon Graphics Inc. .

To define an object in OpenGL a set of transformation matrices has to be defined, in order to have OpenGL map any object co-ordinates into their appropriate screen pixel co-ordinate. Each object is typically made of multiple geometric primitives, such as polygonal faces, wire frame edges, curved surfaces and so on. Each such geometric primitive is drawn by specifying the type of primitive it belongs to and a list of vertices.

The architecture of OpenGL is bound to a specific processing pipeline, but it still allows the user to customise all functions by using standard languages such as C, C++, Fortran, Ada and Java.

Open Inventor

Open Inventor is a library of objects and methods used to create interactive 3D graphics applications. Although it is written in C++, it also includes C bindings. It allows programs to be written by using available building blocks, which enables rapid and effective programming of powerful graphics features. Based on OpenGL the toolkit provides a library of objects that can be used, modified and extended.

The objects offered with Inventor are for example database primitives (shapes, properties, groups and engine objects), manipulators (handle box and trackball), components (material editor, directional light editor and examiner view). In addition to simplifying application development, Inventor facilitates moving data between applications with its 3D interchange file format. Open Inventor also serves as the basis for the VRML standard (appendix 14.3)

Some of the above listed programming languages were developed for specific purposes, e.g. VRML for Internet applications, and it is advisable to use them within their context. Based on the outcome of the task definition and the design parameters each language should be evaluated for its suitability. Fundamental tasks of the visualisation tool, as described earlier, can be coded with Java3D or VRML. However, Java3D will provide more functions for the creation of interactive 3D graphics, and ensures true platform independence. If the visualisation tool is to be used for the dissemination or sharing of information via the Internet, VRML would be a better option, since it integrates very well. However downloading times, the complexity of programming mathematical functions and especially access issues need to be addressed.

7.4 Summary

The objective of chapter 7 was to give an introduction to the philosophy of scientific visualisation and to present a methodology for the combination of visualisation tools and information systems.

3D displays are closer to the human experience of the real world and data analysis can be enhanced by re-constructing objects three-dimensionally. ViSC is the discipline offering the tools for 3D object reconstruction. The design of the visualisation tool is presented as a process in which the creative process of the human brain is translated into computer language.

The layout of the tool is created by defining the required tasks, describing phenomena and display graphics, and choosing an appropriate programming language.

The issues, which are specifically relevant to the integration of the visualisation tool in the information system, are the overall complexity and volume of the data and the control elements that have to be established to link the tool to the ISIS database. The approach offered in this chapter was the 'IS and Multimedia' approach. The visualisation tool and the ISIS are two independent systems running parallel connected by an interface. Easy data retrieval and the possibility to have more than one display using the same data were the main advantages discussed.

It was explained that the development of the tool has to be strictly focused on the user needs instead of implementing newest technology. It was also mentioned that the goal is to create a tool that is easy to use and useful. Fundamental objectives such as convenience and level of interaction, data precision, problem solving abilities, documentation and stimulation are common objectives to most visualisation tools.

The design of the visualisation tool is influenced by the user and the required interaction with the system and the possibilities which the chosen programming language offers. It was recommended that instead of using a formal design procedure it might be more effective to specify the task requirements by user experimentation allowing a mutual understanding between development team and user community.

In conclusion it can be said that the combination of requirements of a range of specialists, such as archaeologists and conservationists, and the general public in a tool can be rather challenging, specifically when the expectations of the tool vary vastly. Flexibility within the design, the ability to modify the tool according to the users needs at any stage of the design, and the detailed documentation of the structures within the tool are the major components for the successful design.

C Laetoli – An Application

This section of the thesis shows an application for the methodology developed in section B and is structured in the same manner:

Chapter 8 presents the photogrammetric data acquisition in Laetoli from the planning stages to the processing of the data. By reconstruction the trackway and the individual footprints the fundamental spatial data for the ISIS is created.

Chapter 9 introduces the development of the Laetoli ISIS. The project layout for the database design serves as an example for the developed methodology in section B.

Chapter 10 presents the development of the visualisation tools, which are the Web Page and the Laetoli Visualisation tool. Issues such as the choice of programming language, the restriction due to hardware, and the graphical layout of the tools will be discussed.

Chapter 11 concludes section C by giving a short overview of the implementation stages of the ISIS into an existing environment. The results are discussed and recommendations regarding for future developments of specialised information systems are given.

8 Close Range Data Acquisition in Laetoli

Palumbo wrote in the 1995 GCI field report: "The re-excavation of the Site G at Laetoli was an unique opportunity to record the site with a precision that could not have been achieved with the technical means available to the Leakey team."

A photogrammetric plan of 23 footprints in the southern trackway had been developed at the time of the original excavation in 1978/1979, but the way photography of the footprints and mapping of the site had been performed did not allow the generation of an accurate plan. It is estimated that the precision achieved by the 1979 photogrammetric record is less than 3cm. Salomonowicz (1983) argued that it was possible to produce a plot of the site at a 1:4 scale with a 5mm contour interval based on data that had an accuracy of less than 3cm (Salamonowicz 1983).

Up to 1mm plots were generated from the data acquired in 1979, even if the reliability and accuracy of these maps was unacceptable. Therefore GCI decided that a repetition of the photogrammetric data acquisition would be justified. This re-measurement was also supported by the fact, that due to the inaccuracy of the data available the features such as axis of the footprints, orientation and reciprocal distance of the imprints were unacceptably approximate (Palumbo 1995). These features are very important factors in the study of locomotion and gait, and their precision is essential to this aim.

8.1 Project Plan for the Photogrammetric Data Acquisition

The first step in producing a permanent record of the hominid track way site at Laetoli and the development of an ISIS was a digital photogrammetric survey. The data acquisition had to be planned carefully to fulfil the requirements of the GCI and to allow the data to be used as a base for the ISIS to be developed.

For the planning of the data acquisition a number of constraints and limitations of the site had to be taken into account (chapter 2).

One of the major constraints was the time limitation. The site was excavated in two separate sections, the northern and the southern part of the trackway. This was done in two consecutive years, 1995 and 1996. In both years a very short period of time was available to treat and conserve the footprints and each section was then reburied. The survey and documentation had to be done during the time of exposure, which was limited to 25 days each year. For a number of reasons the conservation work had to carry on during the survey, which meant that scientists were busy at all times on site.

The project plan had to take this into account and the work plan had to be designed in such a way, that conservation activities on site could take place, without jeopardising the data acquisition process.

The fragility of the trackway was another limiting factor. All the necessary instrumentation had to stay outside the site border. To cope with temperature variations, humidity and dust the measurement equipment had to be very stable and robust. The equipment also had to be chosen according to its reliability since Laetoli is a very remote location and for some of the items backup equipment had to be considered, since it had to be ensured that none of the equipment failed during the data acquisition time.

It was the objective of the field campaign to acquire extensive photogrammetric coverage of the tuff surface surrounding all hominid imprints in the southern and northern trackway, as well as 54 individual footprints. The photography was to be executed with a digital Kodak DCS420, a metric Zeiss UMK 10 and a conventional Hasselblad camera. Each of the images/photographs had to contain a sufficient number of control points of sub-millimetre accuracy to enable the generation of digital terrain models with contour intervals of 5 mm and 1 mm for the track and the footprints respectively. Accuracies of individual photogrammetric control points had to be in the order of 0.5 mm.

Prior to fieldwork the documents, spreadsheets and computer programs were designed to record and reduce the survey and photogrammetric control point observations, as well as to record the photography. A least squares network adjustment program for the evaluation of the point position of all control points was prepared as well.

A frame with 70 retro-reflective targets was constructed (Figure 48), which doubled as a calibration field for the DCS 420 and Hasselblad cameras and as a control field for the footprint photography.

Control and survey point markers had to be designed and were chosen as black metal disks of a diameter of 14mm and a thickness of 1mm. A self-adhesive retro-reflective disk with a diameter of 6 mm was attached to the approximate centre of each disk.

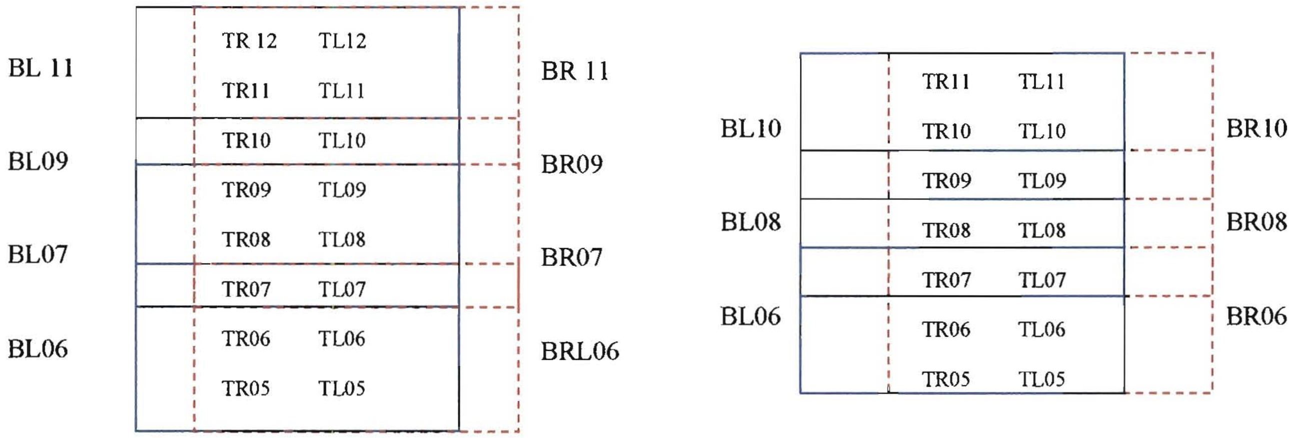
A number of tests and simulation surveys were carried out in preparation for the fieldwork. The photography and DEM generation of the individual footprints was simulated by photographing a footprint in a sandbox using equipment and procedures as close as possible to the conditions anticipated for Laetoli. Both the photogrammetric imaging and the DEM generation proved fully satisfactory.

A least squares pre-analysis of a control point field as planned for the track was processed and resulted in accuracies better than the predicted 0.5 mm.

The control point frame for the individual footprints was surveyed prior to the fieldwork under laboratory conditions using nine images in a bundle adjustment calculation. The photogrammetric survey of these points yielded accuracies below the required 0.3mm precision value.

There was some concern regarding the suitability of vertical angle measurements (as opposed to precise levelling) for the determination of control point heights with an accuracy better than 1 mm. Pre-analysis and a complete survey simulation confirmed that the required accuracies could be achieved by vertical angle measurement. This was later borne out by the results of the actual field survey.

The overall trackway was photogrammetrically surveyed using 31 base lines separated by intervals of 45 cm, which corresponded to the photogrammetric control markers attached to the track surface. The survey was designed to provide complete dual stereo cover for the conventional and digital cameras. A bar was designed on which the UMK and DCS420 camera were mounted for the photography of the trackway, to allow the cameras to 'fly' over the site and to avoid unnecessary contact with the fragile surface.



BR1 ..... BL11 Image numbers

TR1 .... TL12 Control Points

Figure 26 Example of the stereo coverage of the east track section with the UMK 10

Figure 27 and Figure 28 show the design of a single overlap indicating the three camera positions (one on the centre line of the strip and one each on the left and right of the centre line at a distance of half the base line length). The numerical values of the various design parameters vary with the elevation of the cameras above the surface and with the interval between control point lines. Different flying heights had to be implemented on site due to the sloping ground.

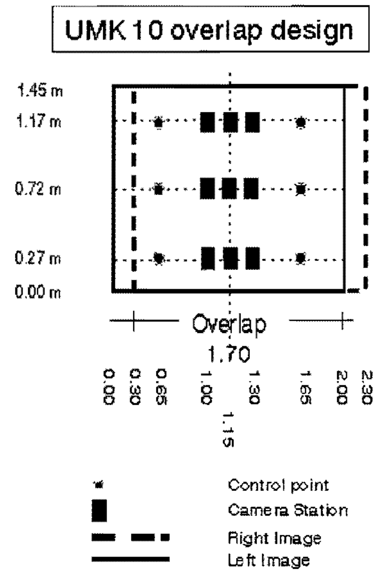


Figure 27 UMK10 overlap for trackway at 1.3 m above ground

nominal focal length	**100 mm**
usable image area	**155 mm by 110 mm**
base line	**0.30 m**
height above surface	**1.30 m**
image scale	**1 : 13**
ground cover	**2.00 m by 1.45 m**
lateral overlap	**1.75 m (85%) by 1.45 m**
along track overlap	**0.85 m (58%) for sequential setups** **0.40 m (27%) for alternating setups**

Table 2 Photogrammetric design of UMK trackway photography

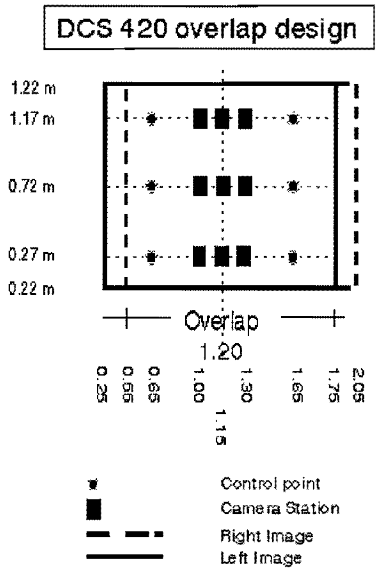


Figure 28 DCS 420 overlap for trackway at 1.6 m above ground

nominal focal length	**14.5 mm**	
usable image area	**13.5 mm by 9 mm**	
base line	**0.30 m**	
height above surface	**1.60 m**	**1.80 m**
image scale	**1 : 110**	**1 : 125**
ground cover	**1.50 m by 1.00 m**	**1.70 by 1.10**
lateral overlap	**1.20 m (80%) by 1.00 m**	**1.40 (93%) by 1.10**
along track overlap	**0.85 m (58%) for sequential setups 0.40 m (27%) for alternating setups**	**0.65 (605) for sequential setups 0.10 (10%) for alternating setups**

Table 3 Photogrammetric design of DCS photography

8.2 Photogrammetric Control Survey

The field survey of the Laetoli hominid footprint track can be divided into three fieldwork components:

- the establishment of a datum (reference co-ordinate system) by means of survey control points
- a conventional high precision survey of photogrammetric control points on the track
- a conventional high precision survey of the photogrammetric control for each individual footprint by means of the control frame.

Originally two co-ordinate systems were established, one for the archaeological survey and one for the photogrammetric survey. These two systems were integrated during the fieldwork to form a single co-ordinate system.

Placing of the photogrammetric control points

The control point markers were temporarily attached to the tuff surface. The points were aligned in two rows of 17 points each on the southern track and in three rows of 13 points on the northern track. 26 points were placed on smaller areas, such as the track of Hipparion imprints.

The targets were placed by tape measurement and not by precise surveying, as the tolerances for target positions were not critical, with the only condition that the points had to be visible in the photography.

Triangulateration of survey control point triangle and data processing

In order to determine the photogrammetric control point positions with sub-millimetre precision, nine external survey control points were placed from which horizontal and vertical angle observations were carried out.

A full triangle observation, including all horizontal and vertical angles as well as all distances (triangulateration) between the nine points. The observations were reduced on site in the prepared spreadsheet in accordance with standard survey methods.

Later the reduced observations were entered into a least squares survey network adjustment. The adjustment results achieved a point position precision better than 0.5 mm.

Triangulation of the photogrammetric control points

The 99 photogrammetric control points were triangulated (using vertical and horizontal angle measurement) from the survey control points. Distance measurements were not possible as neither instruments nor prisms could be placed on the track.

The control point disks were measured by pointing at the targets in the following sequence (Figure 9):

1. Bottom left of the target disk - horizontal and vertical angle
2. Top right of the target disk - horizontal angle

The mean of observations 1 and 2 provided angle readings to the disk centre in horizontal and vertical direction respectively. This observation approach was adopted, as it was not possible to estimate and point directly at the disk centre with sufficient accuracy.

The observations were reduced in the pre-designed and tested spreadsheet. The same spreadsheet served to provide provisional co-ordinates as required for the least squares adjustment.

Height determination and height datum

When determining heights by vertical angle measurement to a precision better than one millimetre, the standard method of measuring instrument heights is not suitable due to its limited accuracy.

To overcome this problem an approximately 3 m long wooden plank was placed in an upright position close to the site and secured with ropes and a concrete base for the duration of the campaign. A 1 m long metal scale (part of a precise tape) was firmly attached to the plank. Every time a theodolite was set up and before vertical angles were observed, a measurement to the scale was taken with the vertical angle set to 90°0 0'0" and 270°0'0" in circle left and circle right position respectively. The mean of the two scale readings was accepted as the instrument height above scale zero.

The arbitrary datum thus established is here referred to as the H-datum. Scale readings were taken every time a theodolite was set up, thus providing precise instrument heights for all setups. The readings were repeated at regular intervals during a setup to guarantee that any accidental movement of the instrument would be noted.

Inspection of the height values, as determined from three stations show excellent agreement with standard deviations better than 0.5 mm, thus confirming the effectiveness of the survey design.

8.3 Photogrammetric Data Acquisition

After the precision survey of all the control markers, the photogrammetric data acquisition began. For each set of images the camera support bar was positioned over the track to allow the camera to be centred over the relevant line of control markers.

Photogrammetry Field Procedures

The field procedures were split in two parts, the photogrammetric data acquisition of the trackway and the photogrammetric data acquisition of the individual footprints.

Photogrammetric data acquisition for the trackway

For the UMK photographs black and white glass plates were used. They were exposed at the appropriate aperture and shutter speed, as determined before each exposure. This was typically f11 and 1/60 sec. The permanently fixed 100mm lens of the camera was focused to the set distance of 1.4 m, which corresponded to the average height of the camera above the trackway.

Images were captured 15 cm to the left and right of, as well as directly above the centre point of the control marker pair. For the hipparion track section only left and right images were captured. The original design to have 6 control points in each image was successfully adhered to and proved to be necessary for the later data processing.

For the DCS420 photography, colour images were captured at an aperture and exposure of typically f11 and 1/250 s. A 14 mm lens was used at a fixed (taped down) and pre-calibrated focal length. As with the UMK photography, images were captured 15cm to the left and right of, as well as directly above the centre point of the control marker pair.

Photogrammetric data acquisition for the individual footprints

Each hominid footprint was surveyed individually to obtain a more detailed map of the imprint. This required the footprints to be photographed within a control frame. The control frame was placed over each footprint in turn and surveyed immediately prior to the photography (Figure 29). The survey of the frame, or rather of four points on it, made it possible to determine the position of the frame and all its control points in the Laetoli co-ordinate system. This was necessary to obtain the footprint co-ordinates in relation to the track.

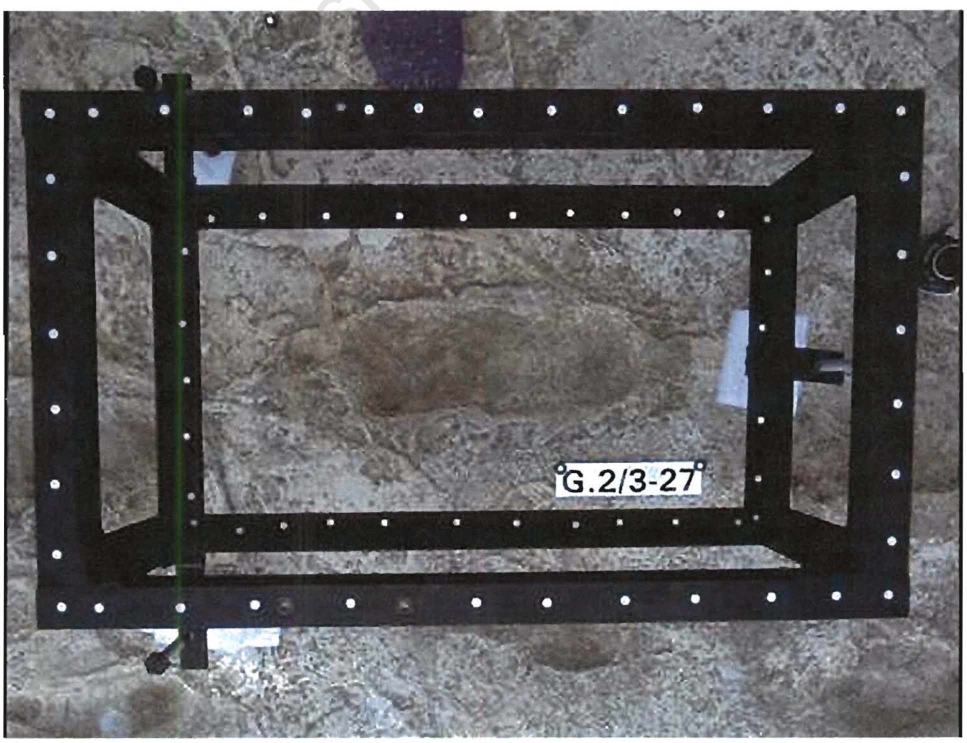


Figure 29 Placing of Control Frame over the individual footprint G2/3-27

Six images of the footprint were captured with the DCS 420 handheld and the control frame placed over each of the footprints in turn, from the approximately symmetrical positions shown in the Figure 30.

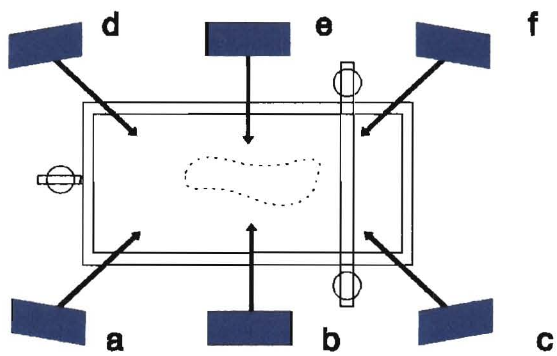


Figure 30 Image geometry for the DCS photography of the individual footprints

The frame was placed on foam rubber to protect the site surface. Image capture was done with the camera handheld at an elevation of approximately 0.8m. Aperture and exposure values were typically in the order of f8 and 1/125 s. A 14mm lens was used and the camera was pre-calibrated at a fixed (taped down) focal length.

Throughout the photography of the footprints utmost care had to be taken to ensure that the frame remained unmoved for the duration of the image capture, as any change in the frame position between images would have rendered the photogrammetric process impossible.

8.4 Photogrammetric Data Processing

The digital and conventional photographic images required a substantial amount of post processing, to produce the required DTMs and ortho-images. Figure 12 shows the process of the photogrammetric data process, which was applied in this project.

The next subchapter introduces the detailed processes, separate for the track and the footprints processing.

8.4.1 Photogrammetric processing of the track images

For the mapping from conventional analogue images of the track (UMK 10) each image pair was mounted in an analytical plotter (Adams Topocart). The relative and absolute orientation of the images was restituted by means of the track control points. Contour lines and spot heights on 'peaks' and in 'valleys' were captured by the machine operator and stored in ASCII format. As a test one model was resurveyed in the analytical plotter by capturing a dense grid of spot heights as opposed to following contours. A DEM was then generated from the spot heights and a contour map was produced using the Arc/Info TIN capability. This contour map was compared with the map produced by direct mapping of contours and no significant differences between the two independent results could be found. A third map of the same area was later generated from the digital images by automated matching methods and again no significant differences could be detected.

8.4.2 Photogrammetric processing of individual footprint images

In order to map the individual footprints it was necessary to determine the positions of the frame control points in the Laetoli co-ordinate system. The frame points 1, 9, 16 and 26 were surveyed and the positions and heights of the surveyed points were evaluated by a least square adjustment and transformed to the Laetoli system.

Once the control point co-ordinates were known in both systems, the points were used as common points in a rigid body three-dimensional transformation to transform the remaining 64 frame points from the local system into the Laetoli system for all the frame positions. The transformations showed average vector displacement of 0.2 mm between the three local frame co-ordinate values and the Laetoli co-ordinates of the same four points (1,9,16,26) after transformation. This confirms the high precision of the fully independent photogrammetric survey of the frame and the in situ theodolite survey of the same four points.

The table below shows typical average standard deviations as derived from the transformation.

	σ_X [mm]	σ_Y [mm]	σ_Z [mm]	σ [mm]
G1-29	0.0925	0.1398	0.0012	0.1676
G1-30	0.1051	0.1058	0.0041	0.1492
G1-31	0.1000	0.1045	0.0011	0.1447
G1-32	0.1566	0.0708	0.0064	0.1720

Table 9: Typical standard deviations for the individual footprints

After inspecting the digital images, it became obvious that the resolution of the DCS images (1524 by 1012pixels), although satisfactory for the automatic generation of DEMs, was less acceptable with respect to visualisation and ortho-image generation. The detail of the tuff surface was significantly better imaged on the scanned Hasselblad images.

A set of four Kodak DCS420 digital images out of the six taken for each footprint was used for the photogrammetric determination of the Digital Elevation Models for each footprint. The four images chosen were those captured from exposure stations above the corners of the control frame (a,c,d and f on Figure 30) as these images provide the best photogrammetric geometry.

The first step in the digital photogrammetric process was the determination of the camera positions and orientations in the overall track co-ordinate system. In a first processing step, the image positions of the control frame targets were located in each of the four images.

The centres of the targets on all four images were then determined by photogrammetric software and used in a bundle adjustment (both in-house software by Rüther, van der Vlugt and Smit) to provide the exterior orientation parameters of the four exposure stations. The interior orientation parameters of the camera were determined using the self-calibration approach. Accuracies achieved in the bundle adjustment can be gauged from the standard deviation; some typical examples are:

	σ [mm]
G1-31	0.0025
G1-32	0.0037
G1-33	0.0092
G1-34	0.0100

Table 10 Examples for bundle adjustment accuracies

Average values for the residuals of image co-ordinates are in the order of 3 micron. These values reflect the agreement between independent data sets of the frame co-ordinates determined earlier in object space and the image co-ordinates of the frame points on the DCS images.

Points of interest, i.e. points representing texture in the images of the footprints, were then located in one of the four images in a fully automated process. The location of these points involves a high pass filter of the image, which serves to enhance the high frequency components in a fairly uniform image. The high pass filtered image is then convolved with a kernel designed to extract gradient changes above a specified threshold level.

Once the interest points have been determined by convolution in the x- and y- directions, they were combined (vectorised), thinned out (Förstner thinning operator) and located to sub-pixel accuracy with the method of preservation of the moment. Points corresponding to the extracted points of interest were then extracted in the remaining three images.

The image matching process employed for the footprints relies on a least squares solution with geometric constraints, i.e. the Multi-Photo-Geometrically-Constrained-Matching (MPGC) technique (Grün 1989), where matching image points are determined together with the object space co-ordinates of the corresponding object points. All software employed for interest point extraction, image matching and bundle adjustment was developed by the Department of Geomatics (Smit 1997).

The results of the image matching process are lists of 3D-xyz co-ordinates in the Laetoli system representing a densely spaced distribution of points which model the footprint being mapped.

The number of point per footprint varied from about 3000 for the smaller of the G1 imprints to more than 13000 for the biggest of the G2/3 imprints. The bundle adjustment result showed image co-ordinate precision of 2 micrometers, again confirming the overall high accuracies of the integrated survey operations.

The number of matched points was largely a function of the size of the selected area, which had to be larger for a bigger footprint or for those not clearly defined in its extent. Thus, the number of matched points is no measure of detail or accuracy. The ratio of successful matches in relation to the points of interest entered into each matching routine was between 89% and 95%, an indication of very good matching result.

After the matching, each footprint was checked with a program which overlays one of the images of each set with a point map showing all matched points. This made it possible to check that there are no areas with poor point density on the selected imprint or its proximity.

The final result of the photogrammetric process is a file of object space co-ordinates X_L, Y_L, Z_L (height) in the Laetoli-System. This file, or rather the point cloud it contains, provides the basis for the DEM and subsequent products.

Accuracies of generated point co-ordinates were derived in the least squares bundle adjustment and all points showed position and height accuracies of better than 0.5 mm and typically 0.2-0.3 mm.

8.4.3 DEM Generation

In general it must be noted that any surface mapping or contouring, be it automated or manual, requires interpolation of the areas between recorded points. This interpolation will lead to inaccuracies and perfect presentation of the object is not possible. The various software packages available for the automated contour/surface generation rely on a range of interpolation algorithms for the 'inter-point' areas the result of which can differ notably (appendix 13.1.5).

For the generation and representation of the DEM and the derivation of numerical and graphical output, a raster DEM was generated by interpolating from the randomly distributed interest points to the grid intersections of a rectangular raster of raster cells, square in planimetry.

For every individual footprint a DEM was calculated and afterwards contour maps with a contour space of 1.0mm and perspective views were produced.

8.4.4 Ortho-Image Generation

Ortho-images were created for each individual footprint and the whole trackway.

The software concept

The ortho-images were produced using in-house software (Rüther, Walker) and software from the Department of Photogrammetry and Remote sensing of the University of Zürich (Baltsavias). The software concepts are:

- The initial dimensions of the ortho-image are determined by scaling the dimensions of the DEM so that the ortho-image covers exactly the same area on the ground as the DEM.
- The xy centre of the ortho-image is determined by taking the centre of the DEM coverage.
- The ortho-image is then produced by finding the pixel in the original image that corresponds to a pixel in the ortho-image. This is done for every pixel in the ortho-image based on the DEM and the cameras interior and exterior orientation elements (appendix 13.1.5).

Interpolation techniques for the rectification

Rectification involves resampling a subpixel. Resampling requires the determination of the greyvalue of a pixel that was shifted in the rectification process. As the rectified pixel will typically not coincide with the centre of a pixel, interpolation is required. A number of interpolation techniques exist to do this. Due to the relatively low resolution of the digital camera the interpolation technique used plays an important role in the quality of the final ortho-image.

The interpolation techniques tested were:

- Nearest neighbour - this produced 'blocky' and inaccurate results.

- Bilinear - the results of this technique did not have the pixel (block) characteristic of the nearest neighbour method, but at the larger scale pixel blocks became visible at the steep edges of the imprints.

- Bicubic splines - this method produced a smooth and accurate ortho-image, even at large scales.

Therefore the bicubic interpolation was employed to resample the image.

For the images from the DCS420 the resolution (1524 by 1012 pixels over a chip area of 13.8 by 9.2 mm) proved, as mentioned earlier satisfactory for the automated DEM generation but was not acceptable with respect to definition of detail. An attempt was made to improve the visual image quality by image processing techniques and in addition to the original 354 images, two sets of the enhanced images were produced using "Image Magick" software. The first enhancement consisted of a normalisation followed by a sharpening operation with a 90% sharpening factor. The second enhancement was done by equalising the image, this enhancement emphasised edges, roots and cracks in the surface.

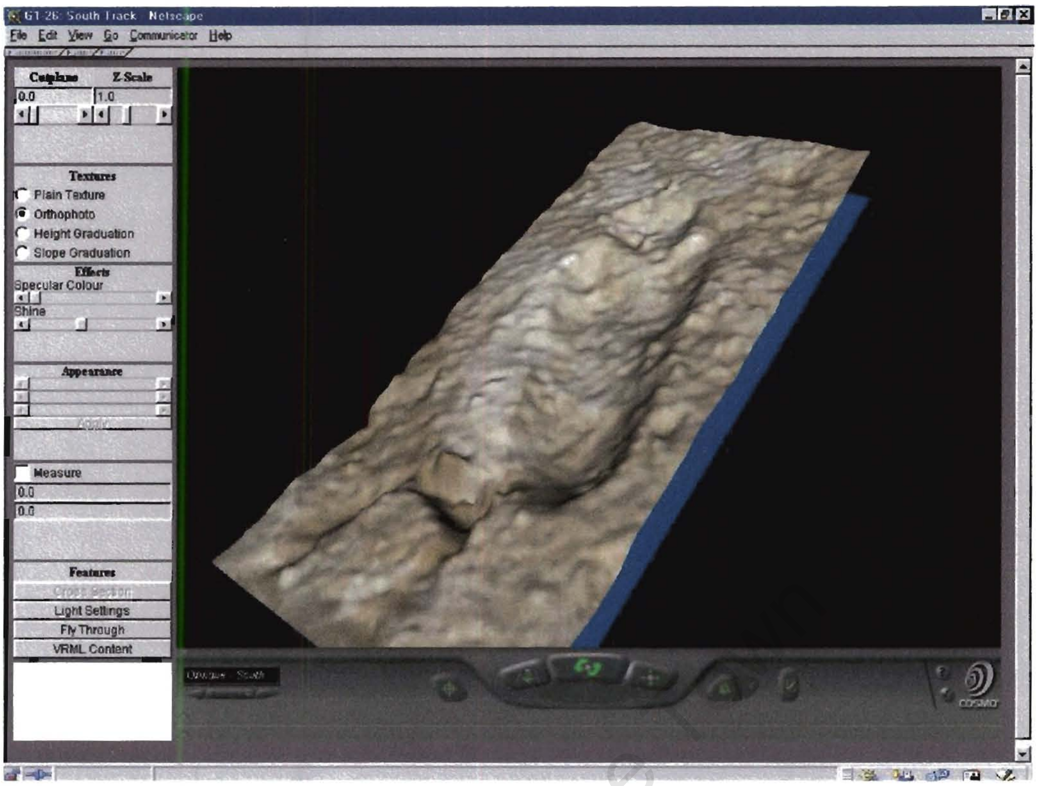


Figure 31 Ortho- Image overlaid on the DTM in the VRML Visualisation package

9 The Integrated Spatial Information System – The Laetoli ISIS

The Laetoli ISIS is a system for the management and dissemination of data collected during GCI field projects, for which the Laetoli site served as a test site for future developments of similar applications.

One objective of the prototype was the development of a spatial data visualisation component. Another was the development of sound methodologies for the dissemination of information to a broad range of users including "conservation professionals, archaeologists, palaeo-anthropological and palaeo-onthological specialists, those interested in the computer application of photogrammetry, GIS and CAD, a variety of students and the general public" (GIS Team 1998).

The project was a collaborative venture between the GCI and the Department of Geomatics. Team members of the GCI contributed with subject expertise on archaeology, conservation, material science and related disciplines. The Geomatics team provided the design of the ISIS, the technical support and guidance during the development phases leading up to the implementation of the system.

The ISIS started in 1998 with the design of an overall GCI information system, in which the Laetoli ISIS was to be embedded. The ISIS was designed independently of the GCI management system at the Department of Geomatics of the University of Cape Town.

At the beginning of 1998 it was decided to include a Web page and a visualisation tool as part of the Laetoli ISIS.

The system was handed over in the beginning of 2000. The following chapter introduces the development of the ISIS as well as the visualisation tools. It is organised according to the layout of chapter 6.

9.1 Design of the ISIS

Since the Laetoli ISIS was developed as part of an overall Information Management System, it was constructed with modularity in mind.

The design vision was to create an interactive visual document of the Laetoli site, which was easy to understand and attractive to a wide variety of users. The goal was to create an innovative way to document archaeological sites while satisfying the requirements of both scientists and general public. One of the chief purposes was to enable the extraction of data and the creation of scenarios that were not pre-determined by the system developers.

There were two sides to the GCI's need to organise data in an information system. It had to be used "within the GCI, so that relevant project data is made available to team members, and outside the GCI, both to disseminate project information, and in order to show the potential use" (GIS Team 1998).

The new system was to address the following tasks:

- A data input function for the ISIS that is accessible to a few, selected members of the Laetoli team.
- A module for data analysis, data query and data display
- A dissemination module for data that allows the GCI to share certain functions of the ISIS, such as data analysis
- A module for educational data visualisation

When the project began, the details of the above tasks had to be established. Since the development of the ISIS was done in Cape Town, while the GCI is located in Los Angeles, a constant communication flow had to be ensured throughout the project. Documents were exchanged to allow the two sides to understand each other's expectations and capabilities, and the requirements of the system.

A strategy had to be established to address the various tasks, collect all the required data, and to design a database that could contain the required variety of information and data formats.

The first phase in the development of the ISIS was therefore a situational analysis and the creation of a project plan.

9.1.1 Situational Analysis

For the creation of the ISIS to be successful, it was important for the developers to understand the environment in which the system was to be implemented. The issues that were addressed included defining the system's users, determining the technological maturity of the user group, establishing the required functionality of the system, and setting policies for the dissemination of information.

The GCI had long been interested in making project information accessible to staff, project collaborators, researchers, scholars and the public. This goal had been difficult to achieve mainly due to the following factors:

- information was often dispersed across the world, and was therefore not easily accessed or collated
- users were unaware of existing information
- information was difficult to find
- data was stored in inaccessible databases
- data was stored in a variety of formats, some of them accessible only with special software
- information was often duplicated

- information was not readily shared or disseminated

The GCI had previously addressed some of these issues with projects such as the development of external and internal Web sites, which allowed the public to access publications, newsletters, reports, books, and journals, and allowed staff members to access project documentation, bibliographic databases and general GCI information.

In the design of the ISIS it was considered important to use standards, guidelines and procedures that had already been developed by the GCI, as well as the international conservation, archaeological, and museum communities (Laetoli IMS Project Team 1997).

It became clear through dialog with the GCI that the ISIS had to fulfil not only the function of a documentation tool, but also to reflect the conservation tasks that form part of the focus of the GCI.

One of the future concerns of the GCI was that it is a constantly changing environment and requires a system that can be easily adapted, expanded and upgraded. So it became a policy to document the system in detail and design a package which is as interoperable and extendable as possible.

During the situational analysis, a number of data access levels were identified by the GCI and the development team was presented with a layout of the system that was needed. This layout was later implemented in the development of the ISIS.
Table 4 is a general overview of the user rights for reading, writing and downloading files.

Access Priorities	Read	Download	Write	Who
1.	All	All	All	Project Manag. System Admin.
2.	All	Part	Part	Team Member
3.	Part	Part	Part	Consultant
4.	Part	Part	No	Staff/Outside Researcher
5.	Part	No	No	General Public

Table 4 Access Rights to the Laetoli ISIS

The outcome of the situational analysis was the definition of the primary aim for the project, which provided the first outline for further developments.

"The primary aim of this project is to organise the data collected by the Getty Conservation Institute (GCI) during the Laetoli project into a structured database, which will be linked to a SIS (spatial information system) created using ArcView. The SIS will allow geographical data (e.g. maps and ortho-images) to be displayed but will also allow the non-geographical data contained in the database (e.g. condition of the footprints, measures undertaken to discourage the penetration of plant roots into the trackway, etc.) to be accessed. The procedures followed in the creation of the database and SIS will be thoroughly documented so that similar databases and SIS can be created to manage the data collected by the GCI in other fieldwork projects. This will ultimately lead to the development of a Global Information Management System for heritage sites being managed by the GCI" (Overall Management Plan 1998).

9.1.2 Project Plan

During the project planning stages it is more important to find out what the system is supposed to do than how it will do it.

As discussed previously, one of the main reasons that ISs fail is that the users of the systems are not involved in the design process, or are not equipped to use the technology they are given, and do not really know what the system intended to be used for.

To prevent this situation in the Laetoli project study an extraordinary effort was made to understand the users and their requirements.

An overview of the expectations of the end-users was established using a number of different questionnaires (13.2). The User Input System Questionnaire (13.2.3) was used to answer the questions about system scope, system architecture and the security expectations. It allowed the user to give input on what he would like to see and to provide recommendations for the system.

The user profile was established with a User Input Profile Questionnaire (13.2.2), which established who would be the main user group and what technology maturity those users had.

The User Needs Questionnaire (13.2.1) allowed the user to express views on the layout of the database. It enabled the development team to determine the form database navigation should take, what level of automation would be appropriate and which searching features would be preferred.

The GCI chose questionnaire respondents, who included management, researchers and operators. The questionnaire established that the users had an understanding of common software packages and a very clear idea of what the system had to provide. This allowed the design team to address the expectations and requirements of the users and to explain what the system would be able to supply as opposed to what the user wanted it to supply. Issues such as user training, acceptable time frames for the development and the creation of a new computer structure were addressed, and a compromise was found to satisfy both teams.

The next step was to define the system outputs, using again the results of the questionnaires and of the discussions with the GCI.

The final product –as described by the GCI and the UCT team- was configured as:

Internal GCI ISIS	Data collection	ISIS & CAD system
	Analysis	ISIS
	Query	ISIS
	Display	Browser / Intranet
	Dissemination	CD ROM / Intranet (scientific)
Others	Original data analysis	CD ROM (scientific) / Internet / Data Download
	Viewing for educational purpose	CD ROM (educational) / Internet

Table 5 Product Description for the Laetoli ISIS

After determining the nature of the final product the necessary input data had to be decided on, as well as the means by which it had to be processed to achieve the desired results.

The first step in the need analysis was the creation of a data inventory, put together by collecting all the available information and sorting it into categories to create an overview of the input data. Appendix 13.4 shows an extract of the inventory. The collection of this information clarified the processing steps that still had to be completed to prepare the data for the ISIS, and indicated what volume of data had to be handled by the system. At the same time a first selection of data for the database was performed. A systematic study of the relevance of the items of data was carried out at a later stage by GCI and submitted to the design team.

Owing to the physical distance between the system's developers and its users, it was decided that the ISIS would be most efficiently designed using the prototype approach. This entailed the development of a pilot version that fulfilled the established requirements and was based on a database filled with a selected subset of data. This would allow the users to test system and establish missing features.

9.2 Design Specifications and Database Design

The design process entailed a conceptual design and a detailed design of the database.

The conceptual model provides a general overview, while the detailed design produces a complete set of specification of the software modules to be coded.

The evaluation of the questionnaires gave a provisional overview, which resulted in the first of the entity relationship diagrams. The entity relationship diagrams show the conceptual model of the database design. Appendix 13.7 shows a second version after changes have been made to the first layout.

During the design phase the design team had to come to a number of decisions. Hard- and software components were chosen according to the technological experience of the user and the financial feasibility. A major aspect was the possibility of future upgrades of soft- and hardware. It was a requirement to employ commonly used software. Special modules and programs were coded to allow communication between different packages and to enhance their functionality. The design of these modules had to be discussed to avoid conflicts between programs and modules at a later stage.

The detailed design of the database was the main step in the design specification phase. This entailed a description of the used data and the relationship between this data, as well as the design of the user interfaces accessing the database and the procedures for the use of the system.

The database was designed according to the combination approach, described in chapter 6.3.5.

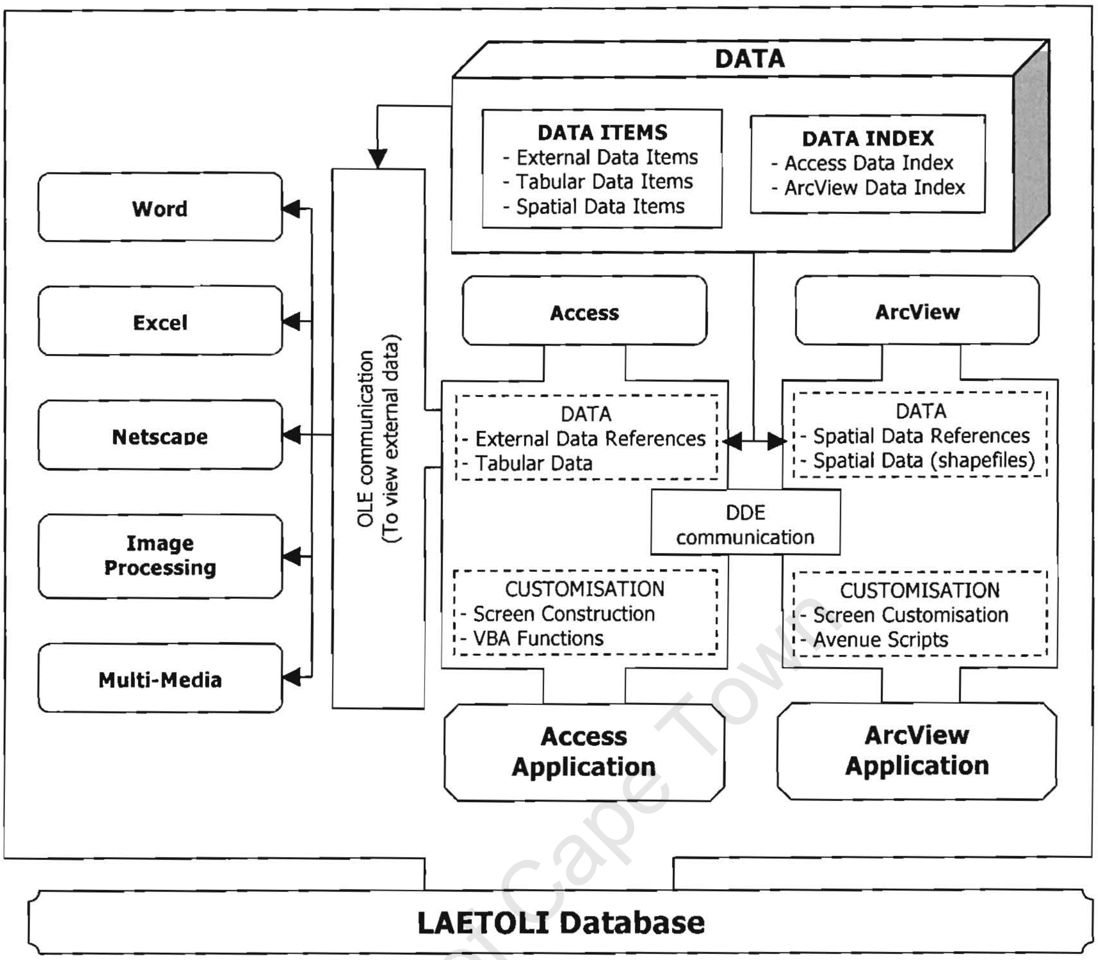


Figure 32 Components of the Laetoli Database (Richards, 2000)

Figure 32 shows a diagrammatic representation of the database components. These components were categorised as being either core or external components. The core components are comprised of the data in the database and the software applications (in this case, Microsoft Access and ArcView applications). The external components entailed the software packages needed to view and edit the non-tabular and non-spatial data.

The data encountered in the Laetoli Spatial Database can be separated into two categories. The first category is the Data Items category, where the spatial data, text, documents, images, tables and other Laetoli relevant information are stored. It comprises a variety of different data formats, such as conventional tabular formats (e.g. Microsoft Access relational databases); geographically, locally and arbitrarily referenced vector data (e.g. ArcView shape files); text documents; spreadsheets; images; and some audio and video material. This data was categorised into three areas:

- tabular data items (data is stored in tabular form in Microsoft Access)
- spatial data items (ArcView shapefiles, e.g. created from AutoCad drawings)
- and external data items (data that cannot be stored in a relational database model, and is kept separate from the database, but can be retrieved using Microsoft Access).

The second category is the Data Index category, where data of different types are referenced according to their application, e.g. shapefiles as ArcView application. The Data Index is referenced by the software applications and allows the recovery of the data.

The inter-application communication is supported by Dynamic Data Exchange (DDE) and the Object Linking and Embedding (OLE) protocols.

After designing the database the design of the user interface and the screen layout had to be done. The users were consulted to ensure that their expectations were met and a manual was written during this process to document the procedures on how to use the system (Richards, 2000).

The screen design was done using several categories as illustrated by Figure 33. The greyed out portion represents the access-restricted areas. These screens cannot be accessed by the casual user and require a password to gain access.

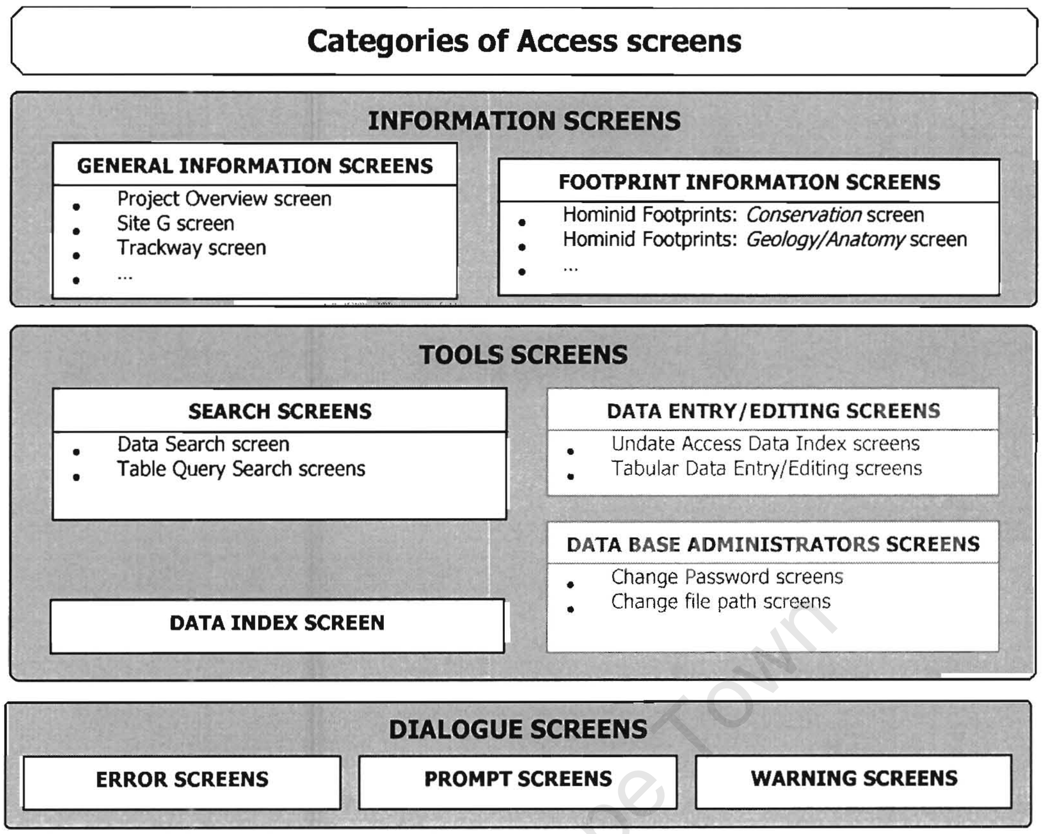


Figure 33 Access Application Screen Diagram (Richards 2000)

For the ArcView application a different layout had to be chosen according to the task performed.

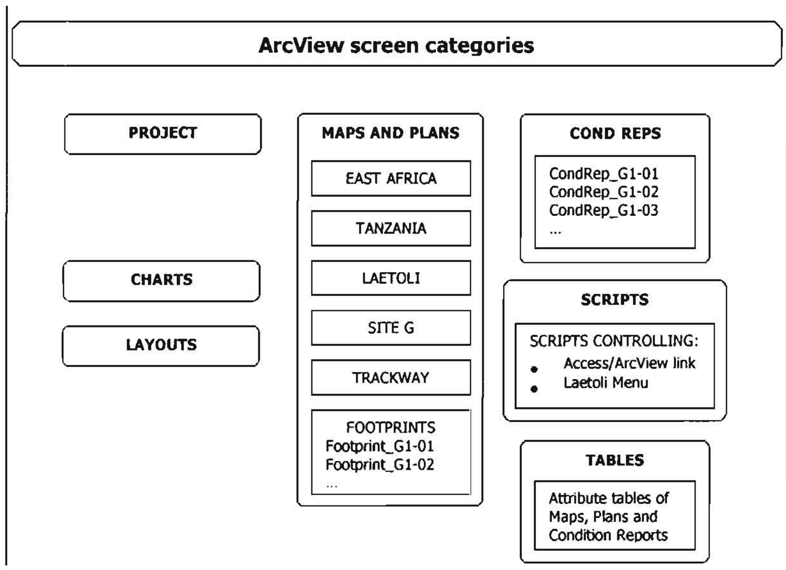


Figure 34 ArcView screen categories

The general user will access the condition reports, maps and plans, and the table and project screen. The system administrator might have to use the script screens.

The navigation through the database is kept very simple. When starting the program the project overview screen appears and supports the navigation with a number of different tabs and buttons as shown in Figure 35.

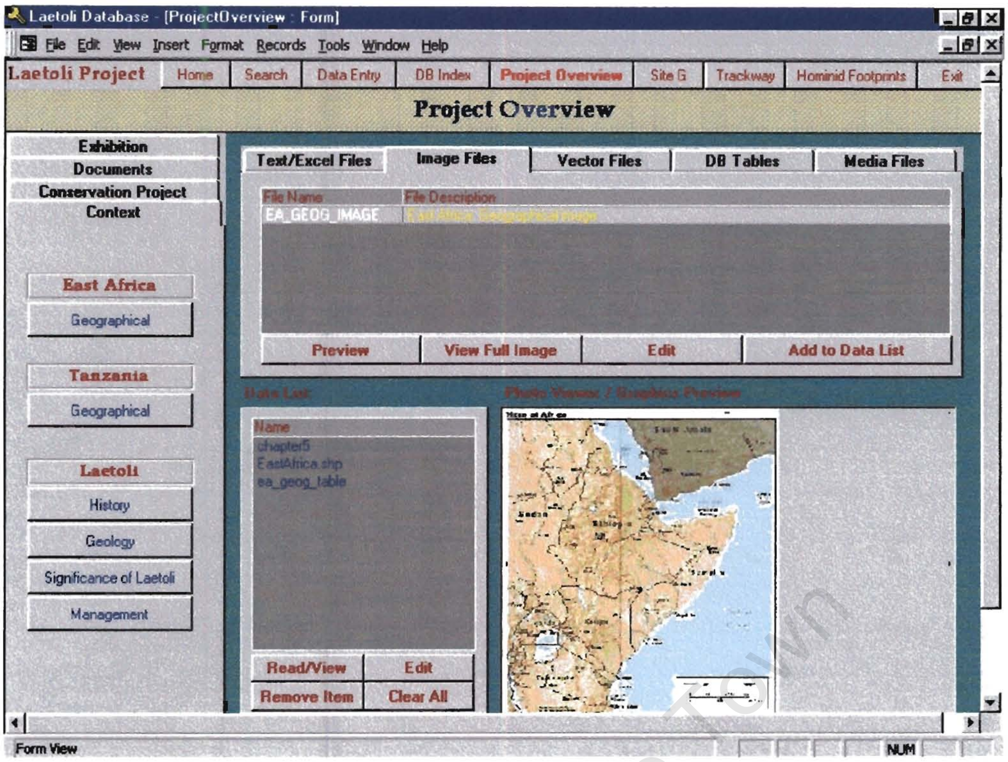


Figure 35 Layout of the Project Overview Screen

If the button **Hominid Footprints** would be chosen the following screen would appear:

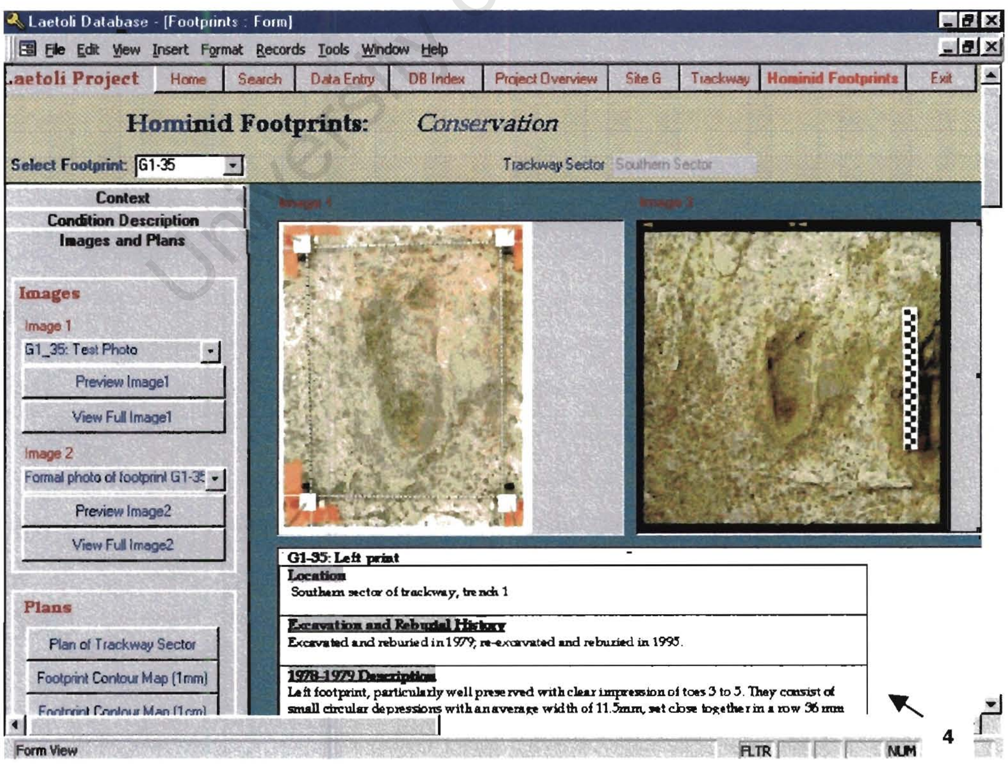


Figure 36 Information Screen Footprints

Certain tasks and functions are better dealt with in ArcView. Therefore a link between the two programs was established. The user can call up ArcView at any time from Microsoft Access, however certain tabs have pre-determined links to ArcView. If the user clicks for example on the screen shown in Figure 36 on any of the buttons listed under the heading **Plans** (bottom left of screen), ArcView will automatically be opened and the following screen will appear:

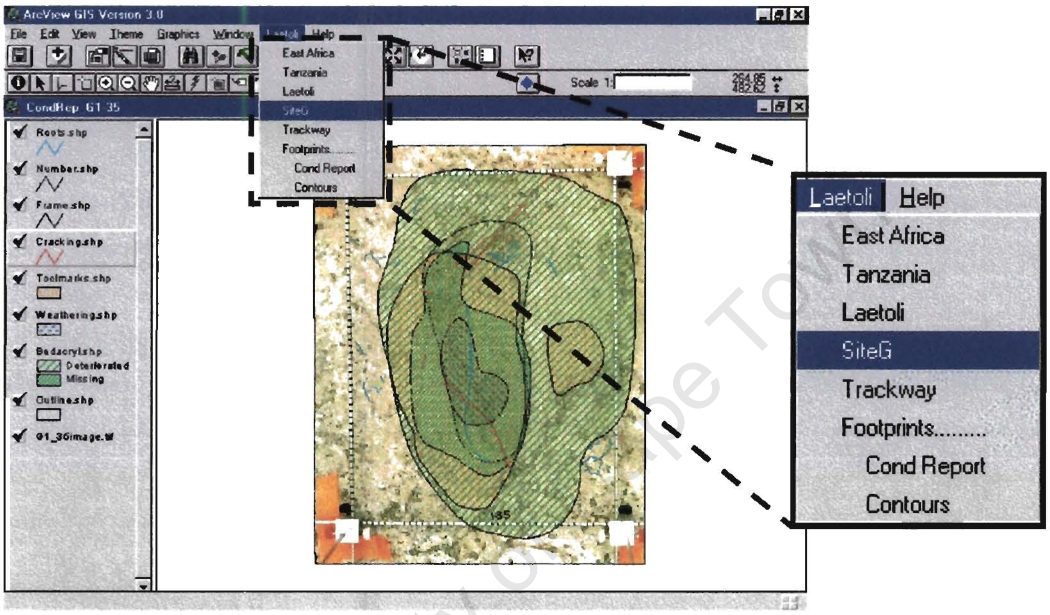


Figure 37 ArcView Footprint screen

This screen shows the overlaid condition reports. By using ArcView buttons, the user could now change to any other footprint or site, while Microsoft Access is still running in the background. By exiting ArcView, Microsoft Access will be restored.

Another application of the combination database was introduced in chapter 6.3.5. Figure 24 shows how ArcView was linked to Microsoft Access, so that textual information can be displayed on the same screen but in different windows as the ArcView application.

All screens are kept in a similar layout to create an environment the user gets very quickly used to.

After designing the database and the layouts, a pilot test was started. The users tested the database thoroughly and various changes were made. The concerns were generally of archaeological nature and required the knowledge of specialists.

The users felt that the system had the required flexibility and allowed a fast and detailed data retrieval. The system was also successful in view of user training. Due to simple window structure and a detailed handbook no specialised training was necessary. The database administrator can with a sound knowledge of Microsoft Access and ArcView, easily maintain the database.

10 The ISIS - Visualisation Tool

As described in chapter 7.3 the challenge of designing a visualisation tool embedded in an ISIS can be broken into two independent issues:

- The overall complexity and the volume of data
- Assignment of the data to the control parameters of the visualisation tool

In the case of Laetoli a vast amount of spatial data and metadata was available and it had to be established which of the data was to be linked to a visualisation tool. The GCI required a Web Page and a visualisation tool that would allow a more detailed view of the data, but could still fit on a CDROM for general distribution. The fundamental objective for the visualisation tool was to create a spatial impression of the site and create a tool that allows the specialist and the general public to 'visit' the Laetoli site.

Due to the complexity and the volume of the data it was decided to keep the Web Page separate from the Laetoli database at this point in time, mainly because of security and access rights issues. There are a number of advantages in creating a Web Page with its own database:

- the data can be presented as a representative selection
- downloading speed is increased
- access rights and security are not an issue.

The Web Page was designed as an independent information source and the information to be shared on the Internet was chosen by the GCI.

The visualisation tool (VT) that was to be part of the Laetoli ISIS was designed with the objective to serve as a window to the virtual Laetoli site. Due to the vast amount of non-spatial data, it was decided to run the visualisation tool as its own entity, allowing any visual data to be displayed, but not to be embedded within the database system. The two systems can be run at the same time, and data can be displayed simultaneously on the screen. The advantage of this is that the visualisation tool only accesses the visualisation data and does not need to deal with any textual or information software. It also allows the more efficient organisation of data, which avoids 'hanging up' of the system.

Before the design of the visualisation tool a detailed project layout was prepared defining the tasks the tools had to fulfil, what phenomena had to be displayed, what graphical layout to chose for the interfaces and what programming language to choose.

10.1 Task Definition

Due to obvious reasons it was decided to aim the Web Page at a wide audience and to equip the visualisation tool with the necessary functions for the scientific audience.

Some fundamental objectives were valid for the Web Page and the VT. For example, convenience and interaction were an important pre-requisite for both tools. Since the audience using these tools cannot be expected to be familiar with computer visualisation, the tool layout was designed to be self-explaining and user friendly.

Another objective was the provision of spatial research tools. Functions such as the overlay of contour lines onto surface, the provision of measurement tools and the display of gradient colours had to be implemented.

After the first design stages the tools were sent to the GCI to allow the future user to test the level of convenience and interaction provided. At a later stage in the development, the effectiveness of the tools was tested by archaeologists from the Department of Archaeology at the University of Cape Town, who were not involved in the project and offered some very valuable objective criticism.

10.2 Approaches

One of the more difficult decisions that had to be made for the development of the visualisation tools was the choice of the programming language. As stated in chapter 7.3.2.2 the main languages that can be considered for these kinds of visualisation are VRML, Java 3D and the OpenGL approach.

An analysis of these packages resulted in selection of VRML for the Web Page and Java3D for the VT.

The following subchapters explain in more detail the different layouts.

10.2.1 The Web Site

Since it was the objective of the project to effectively display spatial and attribute data of the footprints and to share this information as widely as possible, the obvious solution was to create a web site and allow public access to it via the Internet (Taylor 2000).

The organisation of the data for the use on the Internet had to be investigated, since it is not practical to display all the project's data on the Internet, or to connect the ISIS to the Internet. It was decided that the web site would be split into a "static" and a "live" part. Static web pages display information that cannot be modified by the user and the layout is designed to show pre-determined scenes. Most of the text information on the footprints, maps, and images were displayed on the static web page.

The live web page is the interactive part. Here the user can interact with the data and create new, i.e. not pre-determined, information. Thus the data has to be modified by the program according to the user's needs.

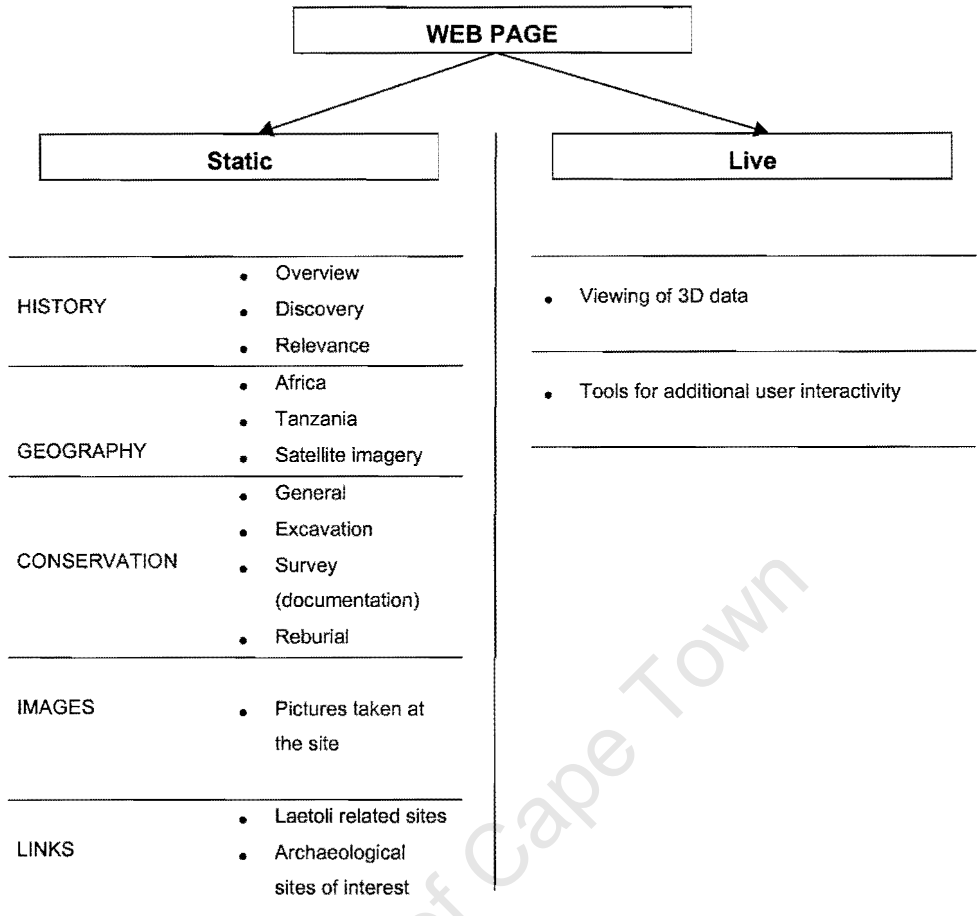


Figure 38 Layout of the ISIS web site (Taylor 2000)

An HTML editor was used to create the static web page, using some basic guidelines to make it easy to access and to read the data. It was established that the most popular pages on the Internet are not - contrary to all expectations - those that have the best graphics or the latest animations, but rather those that have a clear structure, an interesting content and are not overloaded with information. The aims of the static pages were to provide the required information in a simple manner, and to create a structured layout that allows an easy location of the required information.

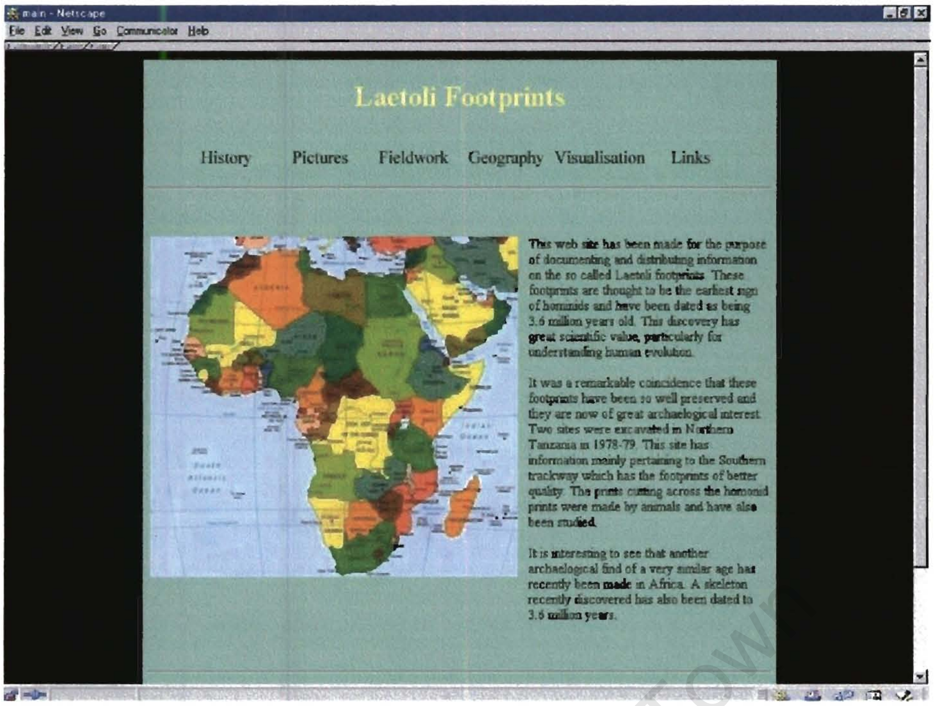


Figure 39 Main Page of the Web Site (Taylor 2000)

The headings "History", "Pictures", "Fieldwork", "Geography", "Visualisation", and "Links" lead from the home page to the web pages containing the specific information implied in the headings. The image of the map is an animated GIF-image, and changes automatically every six seconds to show other images such as the environment of the site, close ups, landscapes and so on.

The live web pages are activated when the user chooses the button "Visualisation". To allow a connection between the HTML-documents (main Web Page) and the visualisation tool, the tool itself was programmed in Java.

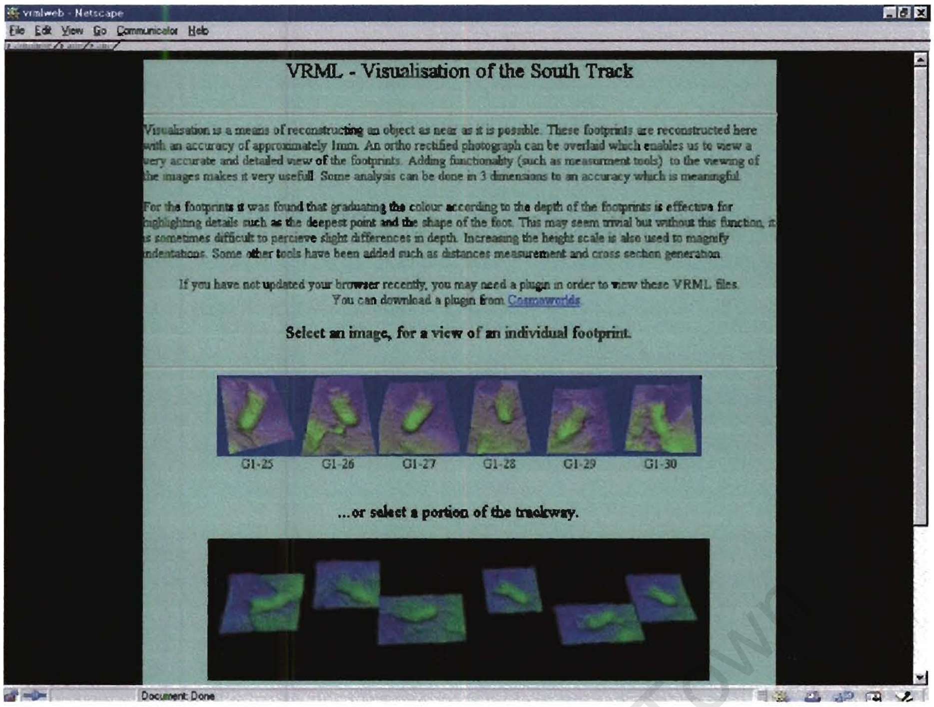


Figure 40 Live Part of the Web Page – the Visualisation (Taylor 2000)

Once one of the footprints is selected a new screen is activated, showing the visualisation interface using a VRML environment.

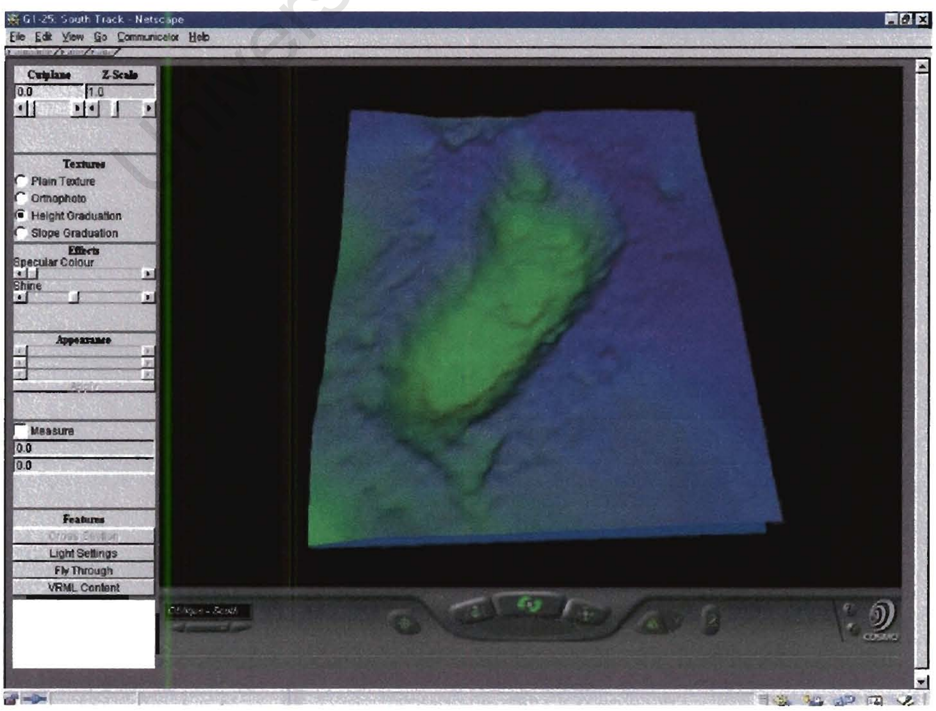


Figure 41 Visualisation Tool Screen – G1-25 footprint (Taylor 2000)

Various functions were designed for the tool, some of which will be explained below. More detail can be found in Taylor 2000.

- Graduated Colour

  Graduating the colour according to varying height levels supports the three-dimensional impression of the objects shape (graduated colours applied on footprint G1-25 in Figure 41).

- Texture Overlay

  3D surfaces can be overlaid with spatially referenced 2D images. Generally, ortho-images are overlaid on the DTM of the same area, since the 3D and 2D information should be free of geometric distortions (Figure 31, pg. 130). This combination allows the creation of a realistic scene, showing the topography and original texture of the object.

- Viewpoints

  Viewpoints are a means of regaining orientation when the user becomes disoriented. The positions and orientations of viewpoints to which the user can "jump" are specified. Three oblique viewpoints and one top viewpoint can be found in the display.

- Multiple Objects

  It is possible to display more than one footprint in the same scene while maintaining their relative position and orientation to each other (Figure 39, pg. 150 bottom part shows 6 footprints displayed next to each other).

- Height Exaggeration

  The height can be exaggerated while the horizontal scale stays uniform. This allows the user to determine peaks and valleys more easily and supports the detection of small height changes. A shadow effect can also be achieved in this way.

- Flood Plane

  The flood plane is a horizontal plane that can be moved through the surface model and is visualised by 'filling' the footprint with water. The plane is transparent enough to see the detail of the areas below the plane level (Plate 1, Appendix 14.1). This visual cut plane represents the outline of the footprints as a contour line at any required height.

- Gradient Highlighting
  Gradient Highlighting is a technique whereby different slope gradients are displayed in different colours ranging from red for very steep to white for a level gradient (Plate 2, Appendix 14.1).

- Distance Measurement and Cross Sections
  This tool allows users to measure 2D and 3D distance between points determined by positioning of the cursor (Plate 4, Appendix 14.1). Cross sctions along a user-defined line can be calculated and are displayed as profiles (Plate 5, Appendix 14.1)

- Fly-through
  A fly-through was created to 'fly' the user through the scene, along a route defined by pre-defined viewpoints. This is especially useful for the inexperienced user, who is not necessarily interested in the scientific tools of the Web page.

10.2.2 The Java Application and the Integrated Visualisation Tool

The analysis of the software packages VRML, OpenGL and Java3D resulted in choosing Java3D for the creation of the VT. This was due to the fact that VRML files require a browser to display their content and the creation of interactive tools is far more complicated. The OpenGL method was rejected since an external programming language such as C++ is necessary and this would result in the application being limited to a single computer platform (Rozendaal 2000). However, some research was done using C++ and the results can be found in the appendix 14.3.

The creation of 3D graphics using Java3D is based on the creation of virtual universes in which the objects are placed.

For the VT the spatial objects, e.g. the footprints, were defined by the acquired DTM's and can be displayed in the Java 3D universe in four ways: scatter of points, wire frame, a filled polygon or a shaded surface model. The choice of display effects the rendering speed and the realism of the models. With increasing realism of the object, the rendering speed decreases. The solid surface model was chosen for the display of the footprints since it is the most realistic representation even though the rendering speed is slower for this approach than for the other displays (Rozendaal, 2000). The user has the option to change to a point or wire frame display.

When starting the tool the user will find an easy-to-navigate window, in its structure very similar to the Web Page layout.

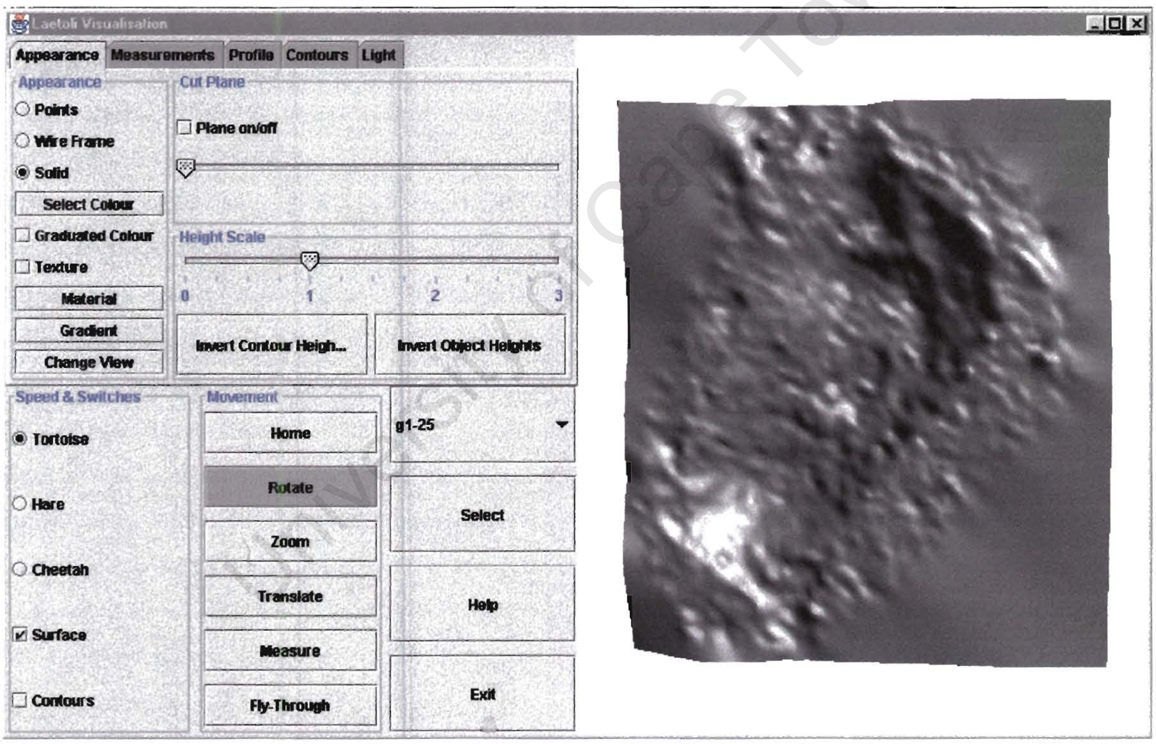


Figure 42 Main menu of the Laetoli visualisation tool

The user can chose between the three appearances: points, wire frame and solid. As mentioned previously this choice has a direct impact on the rendering and processing speed.

In order to enhance the visual appearance a colour value can be applied. Additionally the user is able to drape the ortho-image onto the 3D surface or overlay contour lines.

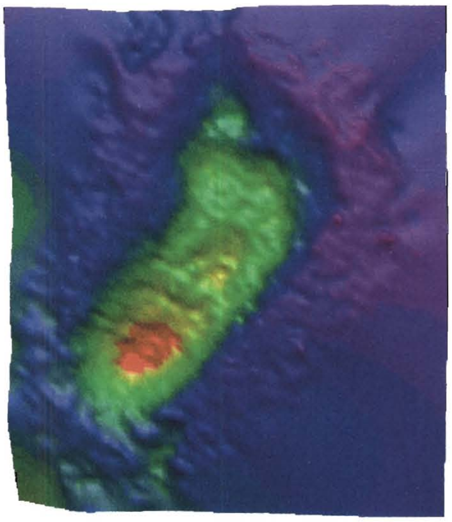


Figure 43 Footprint display with graduated colours

Movement tools are made available to the user to allow interaction with the 3D models and to view the objects from different perspectives. Directional and point light sources allow the user to highlight different features on the 3D surface.

A number of interactive tools were implemented as for the web page (appendix 14.2):

- A cut or flood plane
- Exaggeration of heights
- Measurement tool (distance measurement, profile creation, calculation of gradients)

Computer hardware capabilities limit the possible detail that could be achieved. The recommended hardware for this visualisation tool is a Pentium II 333 with a Riva TNT 16Mb AGP graphics card, which results in rendering speed of up to seven frames per second (Rozendaal 2000). To run the Java application on different platforms a run-time environment is required. These are available on platforms such as the Win32 and Sun platform (Rozendaal 2000).

11 Summary of Section C

The objective of section C was to present a pilot project for the methodology developed in section B.

Chapter 8 showed how close range photogrammetry is used to acquire and process data to use as base data in an ISIS. The detailed description of the planning stages illustrated that the constraints and limitations of the site should be taken into account as far as possible, and that the layout has to be flexible enough to adapt to changing situations.

The photogrammetric data acquisition phase was split between the acquisition of data relating to the trackway and the acquisition of images of the individual footprints. Glass plates were used for the analogue photography and scanned during the processing stages to achieve a higher resolution than the DCS 420 imagery could provide.

The description of the photogrammetric data processing phase in chapter 8.4 explained the different procedures for analogue and digital image acquisition and resulted in the production of contour maps, 3D models and ortho-images.

Chapter 9 introduced the Laetoli ISIS. The ISIS design phase illustrated that planning exercises, as described in section B are essential parts of creating a successful information system. Only in the situational analysis did the actual needs of the GCI become clear to the development team. Responses to the questionnaires used during the analysis helped the team to construct a more effective project plan. The database was developed based on the principles associated with a combination database as introduced in chapter 6.3.5.

Chapter 10 described the visualisation aspect, which consisted of the web site and the visualisation tool itself. The vast amount and complexity of the data as well as the various software applications or control parameters used to display the data were described. A short overview presented the layout of the web site and the visualisation tool.

After the design of the system was completed and tested at the University of Cape Town, pilot versions were sent to the GCI and an intensive testing phases was carried out. The scope of the testing phase was limited to a sample set of data. The test included functionality, data input, applications, queries, data access and performance of the system. The results of the pilot project showed that most necessary changes to the system were of archaeological nature, which implied that more archaeological input should have been provided during the design stages.

Before the hand-over of the system a detailed manual was written by Richards (Richards 2000), to serve as a reference book and tutorial document for the user.

The Laetoli Web Page can be visited under the following Internet address:
http://www.geomatics.uct.ac.za/research/laetweb/main.htm

D Summary and Concluding Remarks

The question this thesis attempted to answer was:

How can information technology support archaeologists and conservators by providing a more effective method of site documentation?

The existing methods of site documentation were reviewed and the methodology of digital photogrammetry was described, offering an effective and affordable approach to the collection of three-dimensional data in an archaeological environment. It was shown that the successful data acquisition is dependent on a detailed project plan, the correct equipment and a compromise between the costs and the quality of the data.

Advantages and disadvantages of alternatives, such as Laser Scanning, were introduced and the investigation showed that the photogrammetric method offered satisfied the requirements of the Laetoli site and produced high quality data.

Information technology and its implementation in the archaeological environment was introduced in chapter 6. The management of the acquired data was presented by applying the so-called combination approach. The main advantages of the ISIS presented were its flexibility and effective retrieval of data. The involvement of the future user during the system design proved to be essential in assuring a successful system implementation.

The use of information technology and computer visualisation was specifically explicit in the context of meaningful presentation of the data. The development of a visualisation tool and a web site offered a solution for the dissemination of data and an advanced tool for future research. By using interactive 3D displays the human experience of the real world is translated onto the computer screen. The combination of the 3D tool and the ISIS creates a "virtual" conservation of the site, which can be visited by anybody without destroying precious archaeological evidence. Easy data retrieval, minimised system crashes and independent system administration present the novice user and the specialist with an exciting tool that can be easily handled and maintained.

The conservation and documentation of the Laetoli site was used as a pilot project. It was shown that it is possible to make archaeological sites a public trust, and a new, flexible and dynamic approach for long-term conservation was offered. The positive response of the GCI to the pilot project showed that it is possible to implement a system like this into an environment that is not exposed to information technology on a day-to-day base.

Testing the methodology using the Laetoli data highlighted a number of issues that were addressed in the design of the methodology:

- The Laetoli project was clearly a conservation project rather than a typical archaeological project and could be described as an "ideal case scenario".

- The post-processing of close range data is generally not supported by commercially available ortho-image software packages. Although the software packages claim to allow close range processing, in the case of Laetoli it was not possible to rectify the images. Specialised software developed at the Department of Geomatics of UCT and from the Chair of Photogrammetry of the University Zürich was used instead.

- The development of the ISIS was very much dependent on the input of archaeological expertise. The geographical distance between Los Angeles and Cape Town made it difficult to keep up the communication throughout the time span of four years.

- The combination of different software packages for the ISIS was made more challenging by the rapid developments in the computer industry. Software was upgraded twice during the development process. The claimed communication between different packages could not always be substantiated in practice. This was especially difficult with regard to the conversion of data files and required more time than was expected.

- The 3D visualisation was partially restricted by the hardware limitations.

In conclusion it can be said that the use of a spatial information system combined with a visualisation tool has been successful. The conceptual and computational models developed during the course of these investigations have not only contributed to an improved understanding of the acquired spatial and meta data, but have also shown how the gap between "modest observations and computer calculations" (Gidlow 1999) can be bridged.

This thesis aims at the creation of awareness in the community of archaeologists rather than providing a step-by-step guide for the design of an ISIS. As stated earlier each situation is different and off-the-shelf solutions typically require editing and modification to suit a given situation. The novelty of this thesis and the scientific contribution lie in the creation of a coherent methodology, which presents a solution strategy modifying the standard information system approach to the archaeological environment. Criteria for data acquisition, management and visualisation should support interested individuals in the future to identify problem areas, formulate policies and create a successful ISIS.

It is recommended that further work be carried out in two directions to consolidate on these first results. Firstly, the investigation of an ISIS as an intelligent system (e.g. neural networks) that would allow archaeological expertise to be implemented. Secondly, with an increasing demand for 3D visualisation, to investigate the feasibility of sharing the information system and the visualisation tool via the Internet.

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13 APPENDICES

13.1 Appendix A: Fundamentals of Photogrammetry

13.1.1 Introduction of the Fundamentals of Photogrammetry

This chapter is a brief introduction to the fundamentals of photogrammetry. It is written for non-photogrammetrists and gives an overview of the theory, the basic mathematical algorithms, and some common techniques of close range photogrammetry.
Photogrammetry is defined as "the science and art of obtaining reliable measurements by means of photographs" (Manual of Photogrammetry, 1952). Fundamentally, it enables the extraction of accurate three-dimensional information from the multiple overlapping of two-dimensional images. A very simple example of this principle is illustrated by viewing images in 3D using a stereoscope or watching 3D movies with special glasses. However, there is a difference between these simple illustrations of the photogrammetric principle and the computerised image processing, photogrammetric restitution, surface model generation and display systems that characterise photogrammetry today.

The modern science of photogrammetry, with its emphasis on digital imagery, is often mentioned in the context of computer vision. But the task of photogrammetry lies in the spatially correct representations of a recorded object and, unlike the field of computer vision, the visual display of the photogrammetrically acquired data is only a by-product.

In photogrammetry the relationship between image space and object space is established by means of a camera. The parameters of the orientation of the camera in object space have to be determined (exterior orientation) as well as the geometric parameters of the camera itself (interior orientation), to allow the reconstruction of an object in three dimensions. The following flowchart shows the steps, which have to take place to reconstruct the position and shape of an object by extracting three-dimensional information from imagery.

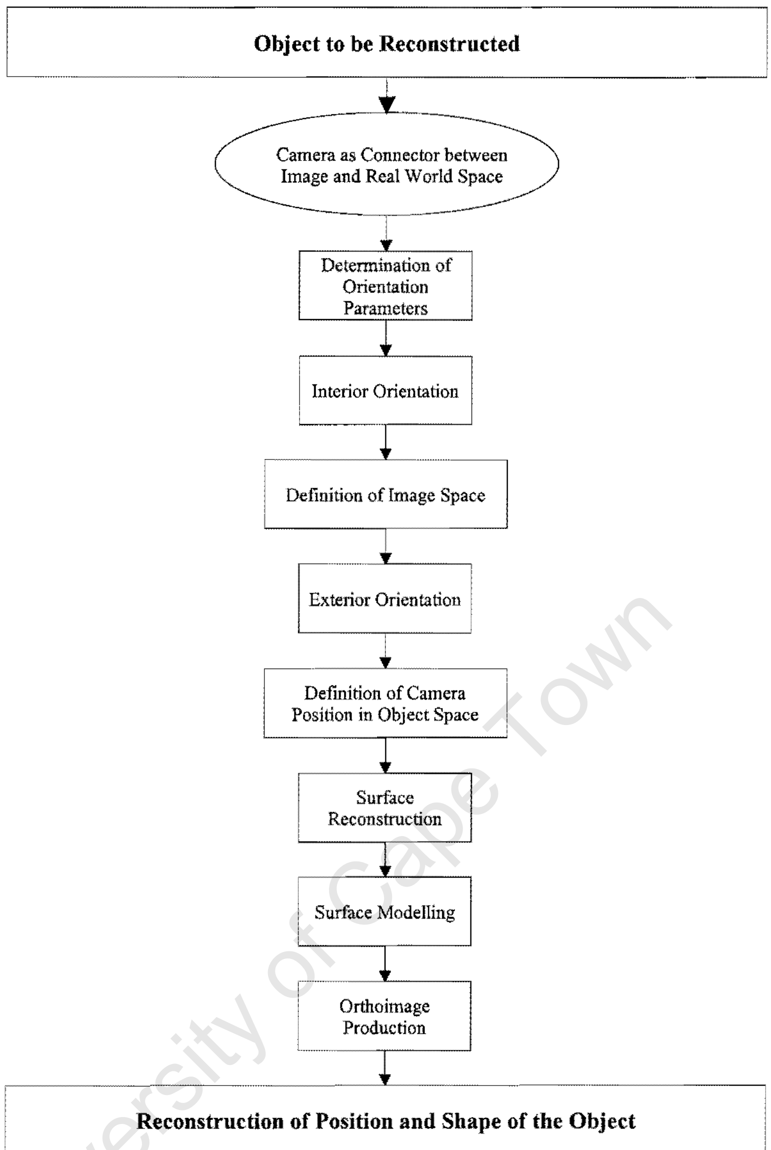


Figure 44 The Photogrammetric Process

Cameras generate images that represent a "central perspective" of the photographed spatial object. This implies that every light ray reaching the surface of the film or chip (in case of a digital camera) during exposure passes through the camera lens. Mathematically, the lens is considered a single point, the so-called projection centre. To reconstruct the position in space and shape of an object from photography or digital imagery, the spatial direction of each light ray and the location of the perspective centre for each exposure must be established with respect to the object co-ordinate system.

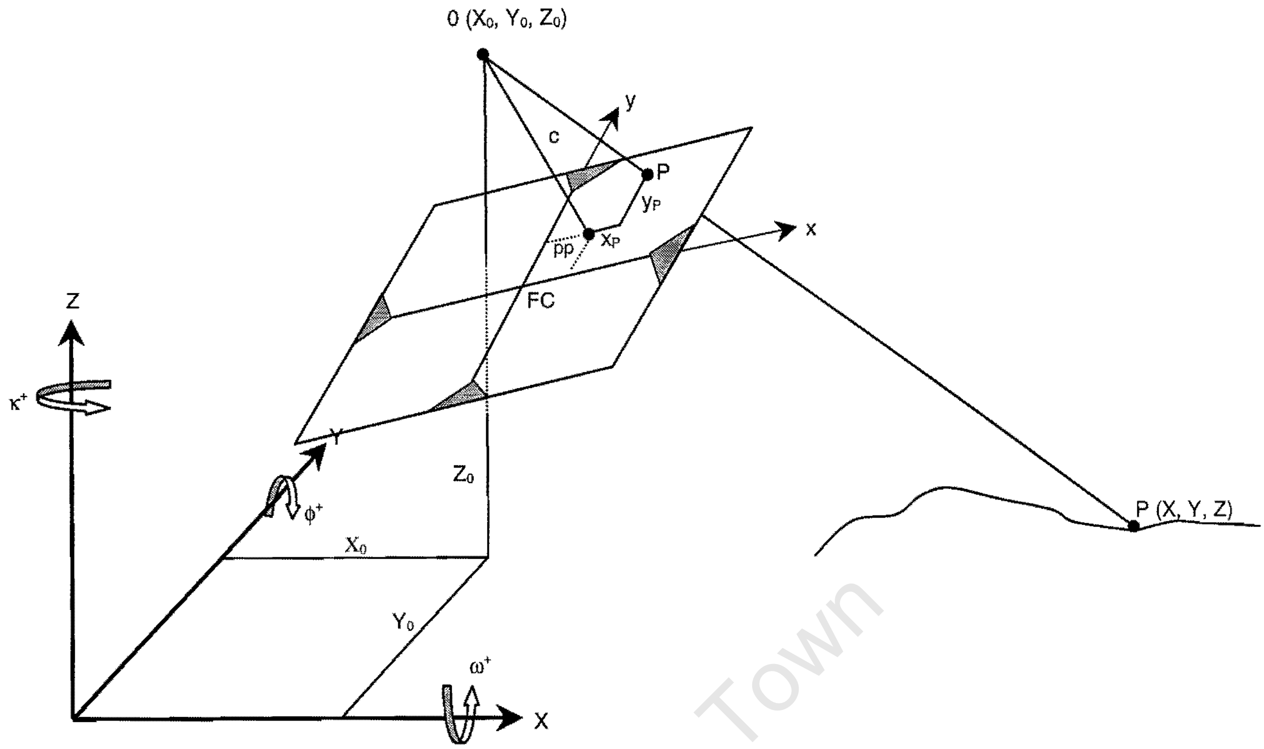


Figure 45 Relation between image and object co-ordinates (Kraus, 1993)

$0 (X_0, Y_0, Z_0)$	Projection centre (camera position)
x, y	image co-ordinate system
P	image point
x_p, y_p	image co-ordinates of P
pp	principal point with the co-ordinates (x_0, y_0)
c	principal distance (camera constant)
FC	fiducial centre (intersection of lines joining fiducial marks)
P (X, Y, Z)	object point
X, Y, Z	object co-ordinate system
ω, ϕ, κ	rotation angles

The internal geometry of the camera comprises of the interior orientation parameters: that is, the co-ordinates of the principal point, the principal distance, the parameters of the lens distortion and the film/chip distortion.

The image co-ordinate system (x, y) has its origin at the principal point pp (x_0, y_0), which is defined as the intersection of the perpendicular from the perspective centre to the image plane. In analogue photographs the image co-ordinate system is physically referenced by fiducial (image reference) marks. The intersection of lines joining opposite fiducial marks defines the fiducial centre FC, which should ideally be identical to the principal point.

In contrast to aerial photography, terrestrial and close-range applications often employ non-metric or amateur cameras. The camera parameters and the image system are defined in the camera calibration process (appendix 13.1.3). The position of the camera in object space - or its exterior orientation - is determined by three orientation angles and three camera station co-ordinates.

The exterior and interior orientation parameters are determined using clearly defined targets with known object co-ordinates. The image co-ordinates of these targets can be precisely measured and the parameters of the orientations can be determined using the relationship between image and object space co-ordinates as expressed in the *collinearity equations* (appendix 13.1.2).

The process of determining the interior and exterior orientation parameters may be achieved in either of the two ways described below:

1. Pre-calibration: The interior parameters are determined with a high degree of accuracy using a set of images of a control field prior to the objects image acquisition. The images of the object are then captured and the predetermined interior orientation parameters are used together with the control point co-ordinates to determine the exterior orientation parameters of the object images. For metric cameras, like the UMK10, the manufacturer of the camera determines the interior orientation parameters. For this reason metric cameras are usually pre-calibrated.

2. Self-calibration: The interior and exterior orientation parameters are calculated simultaneously using one set of images of the object.

After the images have been oriented, several methods can be employed to extract the three-dimensional co-ordinates of the photographed object. Photogrammetric stereo measurements - derived by means of stereo plotters - or digital image matching processes are the most common method used to determine these co-ordinates.

One task of photogrammetry is the production of surface models. That is, generating a representation of a surface object by interconnecting the three-dimensional points to form a network or grid that represents the shape of the object. The combination of the surface model and the oriented image can then be used to create another product of the photogrammetric process, the rectified or ortho-image. It is the orthogonal projection of the original photograph and represents a geometrically and radiometrically correct visualisation of the object, which is created by transforming the image matrix in the camera co-ordinate system into an image matrix in the XY-plane of the ground co-ordinate system.

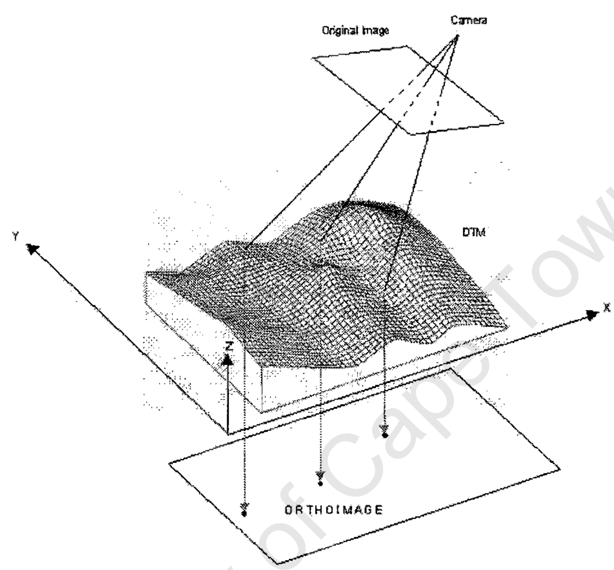


Figure 46 Relation between Image, Ortho-image and DTM

The following chapters explain the process of the object reconstruction from the orientation of the images to the production of the ortho image.

13.1.2 Recovery of the Exterior and Interior Orientation

To determine the parameters of the interior and exterior orientation, the *principle of collinearity* has to be satisfied. This principle states that any object point, the perspective centre and the corresponding image point must form a straight line. The transformation from point (x_i, y_i,-c) in image space to its projected position (X_i, Y_i ,Z_i) in object space can then be modelled by three translations (X_0, Y_0 ,Z_0), three rotations (ω, κ, ρ) and a scale factor s. As described by Kraus (1997) the scale factor varies for each image points in a central projection.

Mathematically the elimination of the varying scale factor is represented by the following equations, in which **s** is the scale factor between the two systems and **R** is an orthogonal rotation matrix with the elements $r_{11}...r_{33}$, describing the relative orientation between the **xyc** image space and the **XYZ** object space co-ordinate system. The point of reference for both co-ordinate systems is the camera standpoint with the co-ordinates (X_0, Y_0, Z_0). In the image co-ordinate system the projection centre has the co-ordinates (x_0, y_0, -c) and is called the principal point (Kraus, 1997).

$$\begin{pmatrix} x_i - x_0 \\ y_i - y_0 \\ -c \end{pmatrix} = sR\begin{pmatrix} X_i - X_0 \\ Y_i - Y_0 \\ Z_i - Z_0 \end{pmatrix} = \frac{1}{s}\begin{pmatrix} r_{11}(X - X_0) + r_{21}(Y - Y_0) + r_{31}(Z - Z_0) \\ r_{12}(X - X_0) + r_{22}(Y - Y_0) + r_{32}(Z - Z_0) \\ r_{13}(X - X_0) + r_{23}(Y - Y_0) + r_{33}(Z - Z_0) \end{pmatrix}$$

Equation 1

By dividing each of the first and second rows by the third row the spatial position of the image in relation to the XYZ object co-ordinate system is established and after some mathematical manipulation and the addition of the correction (dx, dy) of the systematic errors caused by lens distortion, the well known collinearity equations are derived:

$$x_i = x_0 + dx - c \cdot \frac{r_{11}(X_i - X_0) + r_{12}(Y_i - Y_0) + r_{13}(Z_i - Z_0)}{r_{31}(X_i - X_0) + r_{32}(Y_i - Y_0) + r_{33}(Zv - Z_0)}$$
$$y_i = y_0 + dy - c \cdot \frac{r_{21}(X_i - X_0) + r_{22}(Y_i - Y_0) + r_{23}(Z_i - Z_0)}{r_{31}(X_i - X_0) + r_{32}(Y_i - Y_0) + r_{33}(Z_i - Z_0)}$$

Equation 2

The distortions of a camera lens system are generally divided into two types - radial distortion and de-centring distortion. The collinearity equations have to be extended to include these calculated distortion parameters.

Lens distortions can be modelled with Brown's equation (1971):

$$dx = \bar{x}(k_1 r^2 + k_2 r^4 + k_3 r^6) + P_1(r^2 + 2\overline{x^2}) + 2P_2\overline{xy}$$
$$dy = \bar{y}(k_1 r^2 + k_2 r^4 + k_3 r^6) + P_2(r^2 + 2\overline{y^2}) + 2P_1\overline{xy}$$

Equation 3

in which

dx	image distortion of a point in the x co-ordinate direction
dy	image distortion of a point in the y co-ordinate direction
$\bar{x} = (x - x_0)$	x image co-ordinate of a point reduced to the principal point
$\bar{y} = (y - y_0)$	y image co-ordinate of a point reduced to the principal point
r	radial distance between the image point and the principal point
k_1, k_2, k_3	radial lens distortion parameters
P_1, P_2	de-centring lens distortion parameters

Algebraic manipulation of the collinearity equations produces two further methods:

The *direct linear transformation* (DLT) facilitates a transformation between two-dimensional image space data and three-dimensional object space. The advantage of this method is that the transformation parameters are determined without initial approximation. The DLT , as formulated by Abdel-Aziz and Karara (1971), is given by the basic projective equations:

$$x - dx = \frac{L_1 X + L_2 Y + L_3 Z + L_4}{L_9 X + L_{10} Y + L_{11} Z + 1}$$
$$y - dy = \frac{L_5 X + L_6 Y + L_7 Z + L_8}{L_9 X + L_{10} Y + L_{11} Z + 1}$$

Equation 4

x,y	image, or pixel co-ordinates
dx, dy	systematic errors of co-ordinates caused by lens distortion etc.
$L_1 - L_{11}$	unknown transformation parameters
X, Y, Z	object co-ordinates of point

The eleven transformation parameters can be converted into the elements of the interior and exterior orientation. The DLT method generally converges quickly even without provisional values and offers a direct or iterative solution. In the context of the bundle adjustment it is used to determine approximate values for the unknown parameters.

The *bundle adjustment* uses the collinearity condition to transform between image space and object space. In the photogrammetric sense, a bundle is conceived as a set of rays originating at the perspective centre of an image and passing through all points of interest in the image. The image co-ordinates of these points together with the camera principal distance define the bundle. The adjustment principle involves displacing the bundles of rays with three translations and three rotations until the image position of each single point intersects at the correct object space position (Brown 1958).

The unknown orientation parameters and the co-ordinates for each object or control point are established by simultaneously solving the collinearity equations for multiple camera stations. The image co-ordinates of a number of points within the image have to be measured, and good approximate values for the orientation parameters and co-ordinates of the object points have to be pre-determined for the adjustment to converge.

13.1.3 Camera Calibration and the Interior Orientation Parameters

As described in 13.1.1 the interior orientation parameters of the camera are determined by calibrating the camera. Two sets of parameters are established. The first set defines the geometric parameters of the camera itself (principal distance and principal point co-ordinates). The second set comprises the parameters that describe the various systematic errors and distortions, which are the variation between the ideal mathematical model and the physical reality of the system.

An important difference between analytical and digital photogrammetry is the description of the co-ordinate systems. The conventional mathematical co-ordinate system is used for analogue imagery, while the digital image system is based on the electronic characteristics of imaging chips. The digital system - measured in units of pixels - has its origin in the top left pixel of the image. In all of the equations relating to the geometry of image and object space, co-ordinates are required in metric units and related to the perspective centre in the image plane. Thus the measurements made in pixel units have to be transformed to metric units.

Figure 47 shows the difference between the two systems.

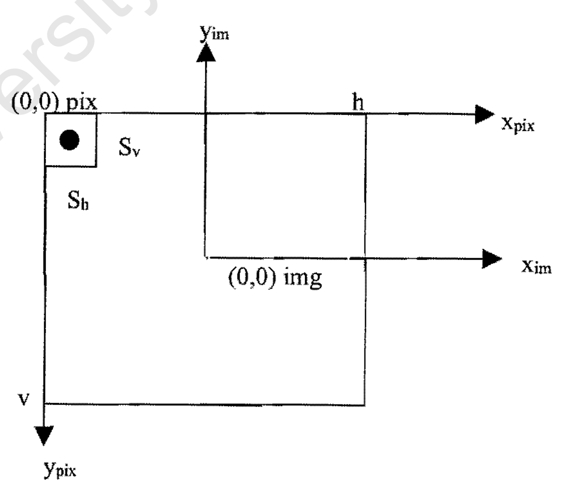


Figure 47 Image and pixel co-ordinate system

The transformation is established by the following equations:

$$x_{im} = S_h\left(x_{pix} - \frac{h-1}{2}\right)$$
$$y_{im} = S_v\left(\frac{v-1}{2} - y_{pix}\right)$$

Equation 5

where:

x_{im}, y_{im}	are the image (metric) co-ordinates of the point
x_{pix}, y_{pix}	are the pixel co-ordinates of the point
h	is the number of horizontal pixels in the image
v	is the number of vertical pixels in the image
S_h, S_v	are the sizes of the pixel in horizontal and vertical directions

It is important to note that the conventions of pixel co-ordinate systems differ. The origin of the co-ordinate system which is the centre of the top left pixel, varies from (0,0) to (0.5, 0.5) and (1,1).

To facilitate the recovery of the interior orientation elements in a calibration process, a control field with a-priori determined control points can be designed. For close range situations the field calibration method can be employed, which makes use of object features or control points with established co-ordinates to calibrate the camera. The advantage of field calibration is that the camera is calibrated in conditions and at a time similar to those in which it will operate.

Frames with pre-surveyed targets are frequently used, allowing calibration in laboratory and field conditions and considering the actually used depth of field.

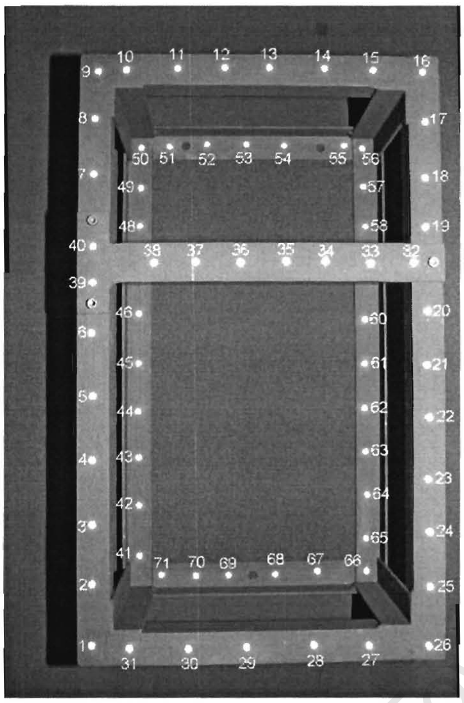


Figure 48 Calibration frame with control points used in the Laetoli project

After the imagery of the control points is acquired, the control points are measured in each image and the calibration parameters are then determined. Digital image processing allows the control points to be identified and extracted using semi-automated or automated methods. The centre of each target can be automatically located with sub-pixel accuracy by employing the weighted centre of gravity method (Trinder 1989, van der Vlugt, 1995).

13.1.4 The Exterior Orientation Parameters

The term exterior orientation refers to the position and orientation of the camera in object space when the image is taken. As stated earlier the orientation parameters are established by defining control points with known object- and image space co-ordinates.

A control frame, similar to the one shown in Figure 48, may be used. The control points should be evenly spread over the image area and have to represent the depth of the object, which can be achieved by having control points at different elevation. Generally it is advisable to use control point frames in applications where the object can be placed inside the frame. The accuracy of the exterior orientation parameters depends mainly on the distribution and accuracy of control points that are available and visible in multiple images.

Some consideration should be given to the design and size of the control points. The targets in the image should be easily and accurately identifiable and should therefore be circles or other features that are clearly distinguishable from its surroundings.

In the case of an automated point detection approach, retro-reflective or bright contrast targets are used. After the targets have been separated from the background by means of thresholding processes, the centre of targets may be calculated using pixel grey levels. Trinder (1989), Xue (1992) and van der Vlugt (1995) report on the area based centring routing which is commonly used and recommended as one of the most efficient and accurate techniques for target centring.

Once the interior and exterior orientation parameters of the images have been determined, the area of interest needs to be extracted from the images to reconstruct the three-dimensional surface of the object.

13.1.5 Surface Reconstruction

As defined in appendix 13.1.1, photogrammetry is concerned with the "accurate extraction of three-dimensional information in object space given the corresponding xy image co-ordinates in two or more photographs or digital images".

In earlier days, surfaces were reconstructed mainly by plotting contour lines on a stereo-plotter. Today spatial data capture and representation of the three-dimensional data is moving more and more towards an automated process, creating the so-called digital terrain or surface model. Digital terrain or surface models (DTM/DSM) can be defined as an ordered set of values, which describes the spatial distribution of topographic or object features.

To determine 3D information from images using automated techniques, the images have to be available in digital form and the interior and exterior orientation parameters have to be known.

A surface in an image is often described by the grey value changes in the surface texture. These changes are used to extract points, which describe the surface and provide a dense irregular grid of surface points. The process used to extract these points is called *interest point extraction* and is based on a variety of algorithms, such as Canny filter, Sobel filter, Maximum Gradient Filter and Moment Preserving. A detailed description of these filters can be found in the relevant literature, e.g. Smit 1997.

Once the points of interest have been located in one image, they need to be associated with the conjugate points in the other images, i.e. the same object point has to be found in all images. This process is called *image matching* and involves the location of some points in two or more overlapping digital images of the same scene taken from different perspectives, thus enabling the computation of the object co-ordinates of the points through space intersection (Smit 1995).

A very effective method for the automatic detection of conjugate or matching points is the Multi-Photo-Geometrically-Constrained-Matching (MPGC) technique, as proposed by Grün and Baltsavias in 1988.
This method is based on area-based matching. It forms a window around the interest point on the reference image and searches the other (or search-) images for an area of minimum difference (in appearance) allowing for possible differences in the rotation, scaling and shape of the search patch due to differences in perspective. The search space on the search images is geometrically constrained by restricting the search to a narrow band around the epipolar line and is executed in more than two images. MPGC also allows for a global difference in the radiometry of the various images. The need for this arises, for example, if light conditions change between images.

To ensure a successful match the matched areas require close approximations. The determination of these approximations can be done in a number of ways. Epipolar geometry is one of the most popular of these methods.

Given two images, the epipolar plane for a point in 3D space is defined as the plane containing this point and the two projection centres of both images as well as the image points. The plane intersects both image planes in straight lines, called epipolar lines. The epipolar line is the theoretical line, which is created by the intersection of the epipolar plane (defined by the two projection centres and the object point) with the image plane. If the relative orientation of two images is known, for a given point in one image, the epipolar line in the other image can be computed and the conjugate point must lie on this epipolar line (Heipke 1996).

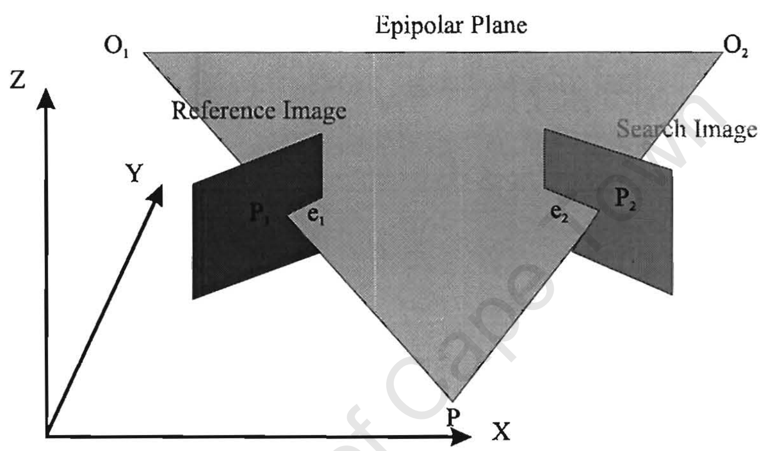


Figure 49 Epipolar Geometry: the epipolar plane O_1, O_2, P and the epipolar lines e_1 and e_2

A refinement to MPGC matching is the use of multi-image correlation (MIC), as proposed by van der Vlugt (1995). This technique further reduces the number of regions in the images where the corresponding points are sought. Incorporating MIC into the matching process reduces the possibility of mismatches due to the added information from multiple images which leads to an increased matching success rate. The theory of feature- and area- based matching is described in detail by Trinder (1990), Baltsavias and Grün (1988, 1991), Wong and Ho (1986).

The data obtained from the MPCG matching is a point cloud and thus, it is not evenly distributed and does not completely represent the surface of the object. To convert the data from point observations to a continuous field modelling a surface, the data has to be interpolated to represent the surface between the matched points.

In the context of surfaces, interpolation is defined as the procedure of predicting the height value of a non-sampled point on a surface from measurements made at point locations within the same area or region . It serves the purpose of estimating elevations in regions where no data exists. The visual representation of the surface data can be modelled by contour lines, discrete regular grids (wire frames) or by triangular irregular networks (TIN).

The accuracy of a derived DTM is defined by the average vertical error of all points interpolated within the DTM grid. The quality of a DTM is comprised of the appropriate description of the surface and the completeness, reliability, consistency and uniformity of accuracy distribution within the DTM (Ackermann, 1996).

Surface Reconstruction, interpolation methods and algorithms are described in detail by Grün et al. 1989, Grün et al. 1993, Ackermann 1996, and Heipke 1996.

13.1.6 Digital Image Rectification

Digital image rectification is a photogrammetric process in which an orthogonal projection of the image is produced. The production of an 'image-map' both the displacement of image features caused by the relief of the object surface and the displacement caused by the tilt of the image with respect to the ground co-ordinate system have to be corrected.

The necessary input data are:

- the digital image
- exterior and interior orientation and, if necessary, other correction values (e.g. lens distortion)
- a DTM of the area of interest

Digital image rectification consists of the transformation of the pixel co-ordinates to their geometrically correct positions and the interpolation of the grey values. Each pixel can be either transformed directly from the image to the ortho-image (*direct method*) or from the ortho-image back to the original image (*indirect method*). The indirect method is more commonly used, since it allows the combination of the geometric transformation and grey level interpolation. A regular pixel position in the ortho-image is defined by its geo-referenced co-ordinates. The height of this point is interpolated in the DTM and the position of the point in the original image is found using the exterior and interior orientation parameters. The grey value for this location is found by the interpolation of the surrounding grey values of the original image to find the grey value for the ortho-image. The interpolated grey value is then allocated to the ortho-image pixel.

Once the ortho-image is produced it can be used for a number of applications. With the growing application of computer visualisation, overlays of ortho-imagery onto DTMs allow very realistic three-dimensional representations of the modelled surface.

13.2 Appendix B: Questionnaires

13.2.1 User Input Need Questionnaire

USER INPUT

NEED QUESTIONNAIRE

This questionnaire tries to determine what functions the user expects of the new ISIS system to be able to perform and which of these functions are most important and will be most used.

1. Rank the methods of navigation through the ISIS listed below in order of preference. (1 = most preferable, etc.)

Menu screens with command buttons	
Menu screens with hierarchical lists	
Pull down tool bar menus	
Tool bar command buttons	
Clickable icons	
Another form of navigation control (please specify)	

2. Rank the levels of system automation listed below in order of preference.

Full automation (predefined queries, load up ArcView with predefined set of maps/plans, etc.)	
Intermediate automation (some predefined queries, some user defined queries, specify plans to load with ArcView using 'connection wizard', etc.)	
Low level automation (almost exclusively user defined queries, specify plans view in ArcView only once ArcView loaded)	

3. Rank the following database functions in order of their likely frequency of use.

Use the following rating scale for the next question:

1 = very important

2 = important

3 = desirable but not particularly important

4 = not important

Data storage	
Data retrieval	
Data viewing/browsing	
Data entry/editing	
Data analysis	

Other (please specify)	

4. Rate the importance of the ISIS being able to have the following characteristics.

Browse capabilities	
Search capabilities (e.g. keyword search)	
Data entry/editing capabilities	
Visualisation capabilities (by linking up to visualisation web page)	
Ability to view text/image/video data from ArcView as well as the main Access user interface	
Ability for users (other than administrator) to access the tables, queries, modules, etc. behind the interface forms	
Ability to import data from a wide variety of data formats	
Ability to export data to a wide variety of data formats	
Own programming capabilities	
Backup capabilities	
Other (please specify)	

5. Assuming it is important to be able to search the database, rank the following search criteria in order of preference.

Keywords	
Subject categories	
Hierarchy (site levels)	
Hierarchy and subject	
Thumbnails (for graphics)	
Data types (text, graphics, audio, file extension, etc.)	
Other (please specify)	

6. List requests for predefined queries you would like the database perform.

7. List requests for reports you would like the database to produce.

13.2.2 User Input Profile Questionnaire

USER INPUT

PROFILE QUESTIONNAIRE

USER PROFILE

This section of the questionnaire is aimed at determining who the primary users of the database will be and their level of technological maturity.

Who will be using the database? (Tick where appropriate)

GCI staff	
Staff from other divisions within the Getty	
Project participants from outside the GCI	
Archaeological researchers outside the GCI	
Interested visitors (with archaeological background)	
Interested visitors (with little or no archaeological background, general public)	
Others (please specify)	

Rank the user categories in order of their frequency of database usage. (1 = most frequent user, 2 = next most frequent user, etc.)

GCI staff	
Staff from other divisions within the Getty	
Project participants from outside the GCI	
Archaeological researchers outside the GCI	
Interested visitors (with archaeological background)	
Interested visitors (with little or no archaeological background, general public)	
Others (please specify)	

Will there be different categories of users within the GCI?

If so, please list these user categories in order of their likely frequency of database usage.

Use the following rating scale for the next question:

1 = Good

2 = Fair

3 = Poor/Vague

4 = None

Rate the technological maturity of the database users according to the skills listed. (Rate both the skills of users within the GCI and the expected skills of users external to it.)

	GCI	Ext.
Basic Windows 95/98 skills		
Word processing skills		
Spreadsheets skills		
Knowledge of GIS concepts		
AutoCAD familiarity (or familiarity with other CAD packages)		
ArcView familiarity (or familiarity with other GIS packages)		
Computer programming skills		

13.2.3 User Input System Questionnaire

USER INPUT SYSTEM QUESTIONNAIRE

The questions in this section are aimed at gathering information on the envisaged operational structure of the system. Naturally, some of these elements cannot be catered for at UCT (e.g. integrating the database into a larger information system), but they may impact on the system design and structure.

System Scope

What is the envisaged extent of the database. (Tick appropriate choice)

A stand alone system to manage data for this project only	
A stand alone system to manage data for this project but linked to and accessible from a larger information system	
Other (please specify)	

If this database is to form part of a larger information system, what is the extent of the larger system? (Tick appropriate choice)

Information system servicing the GCI	
Information system servicing the Getty as a whole	
Other (please specify)	

System Implementation and Maintenance

What will the position be regarding database administration. (Tick appropriate choice)

A designated administrator of the database	
Certain users in the GCI will have administrative capabilities	
Other (please specify)	

Use the following rating scale for the next question:

1 = Good

2 = Fair

3 = Poor/Vague

4 = None

Rate the database administrator's knowledge of the following categories.

Database theory	
Microsoft Access	
Visual Basic / Visual Basic for Applications	
Open Database Connectivity (ODBC)	
Avenue	
GIS theory and concepts	

Does the GCI have support and maintenance contracts with the relevant software vendors (esp. the ESRI and Microsoft vendors)?

(Being able to rely on support from software vendors may be important when implementing the system. More importantly perhaps, their support will almost certainly be needed to upgrade and convert the system when and if a decision is ever made to upgrade the software.)

<u>**System Architecture**</u>

Is the database to be networked or will the whole database and associated applications reside on a central workstation? (Tick the appropriate choice)

Networked	
Centralised	

Assuming a networked system, rank the following architectures in order of likelihood.

Database on central server accessed by individual users from their PCs	
Different data sets stored at different locations (different PCs/workstations), but the user able to access all data sets across a network	
Each user has a replica of the database on their PCs	
Other (please specify)	

Again assuming a networked system, will all users have access to all the software and hardware components needed to view all the information (either by having it resident on their PCs or being able to access it over a network)?

Use the following rating scale for the next question:

1 = All users

2 = Most users

3 = Only a few users

Below is a list of hardware and software components (other than MS Access) which will be needed to use the full capabilities of the database. Rate them according to how many users will have access to them.

MS Internet Explorer 4.0*	
ArcView	
Multimedia Player*	
Kodak Imaging for Windows*	
Java Runtime environment +	
CosmoWorlds+	
Sound card and speakers (for audio data)	

(* Packaged with Windows 98)

(+Only need if visualization capabilities important – see *User Input Questionnaire B (4)*)

Which of the following categories of data should preferably to store inside the database tables (e.g. as memos or OLE objects) and which should be stored in files external to the database.

	Int.	**Ext.**
Maps		
Site Plans		
Attribute tables of plans/maps		
Conservation/Documentation notes		
Photographs (of conservation/documentation/site activities)		
Photogrammetric data		
Video data		
Audio data		
Field Reports		
Glossary		
Bibliography		
Other (please specify)		

Security

It may be that there is sensitivity associated with certain data in terms of who can view, edit or delete data. In order to protect these data they need to be identified and security controls need to be implemented.

Use the following rating scale for the next question:

1 = view, edit and deletion restriction

2 = edit and deletion restriction

3 = deletion restriction

4 = no restriction

Rate the type of restrictions required for the following categories of data.

Maps	
Site Plans	
Attribute tables of plans/maps	
Conservation/Documentation notes	
Photographs (of conservation/documentation/site activities)	
Photogrammetric data	
Video data	
Audio data	
Field Reports	
Glossary	
Bibliography	
Other (please specify)	

Rank the following types of security controls in order of desirability.

User groups: Set up user groups where each user group has a user profile. The user profile determines the access rights (e.g. view only, view/enter data, full administrative rights, etc.) to data.	
Passwords: Type in passwords when the user view/edit/enter/delete data.	
Other (please specify)	

13.3 Appendix C: Evaluation of Questionnaires

USER INPUT QUESTIONNAIRE A

Respondent's Name(s): Laetoli GIS team

USER PROFILE

This section of the questionnaire is aimed at determining who the primary users of the database will be and their level of technological maturity.

1. **Who will be using the database?** (Tick where appropriate)

GCI staff	✓
Staff from other divisions within the Getty	✓
Project participants from outside the GCI	✓
Researchers outside the GCI (anthropologist, archaeologists, conservators)	✓
Interested visitors (with professional background)	✓
Interested visitors (with little or no professional background, general public)	later
Others (please specify)	

2. **Rank the user categories in order of their frequency of database usage.** (1 = most frequent user, 2 = next most frequent user, etc.)

	During project	**After project**
GCI staff	1	3
Staff from other divisions within the Getty	4	5
Project participants from outside the GCI	2	4
Researchers outside the GCI	3	1
Interested visitors (with professional background)	5	2
Interested visitors (with little or no professional background, general public)	6	6
Others (please specify)		

3. **Will there be different categories of users within the GCI?** <u>YES</u>

4. **If so, please list these user categories in order of their likely frequency of database usage.**

Project staff
Conservation and Scientific staff
Project managers and supervisors

Administration

Use the following rating scale for the next question:

1 = Good

2 = Fair

3 = Poor/Vague

4 = None

5. Rate the technological maturity of the database users according to the skills listed. (Rate both the skills of users within the GCI and the expected skills of users external to it.)

	GCI	**Ext.**
Basic Windows 95/98 skills	1	2
Word processing skills	1	1
Spreadsheets skills	2	3
Knowledge of GIS concepts	3	3
AutoCAD familiarity (or familiarity with other CAD packages)	3	3
ArcView familiarity (or familiarity with other GIS packages)	3	3
Computer programming skills	4	4

NOTE: The Getty's Information Technology Department is able to provide training in many of the above-mentioned areas.

THE SYSTEM

The questions in this section are aimed at gathering information on the envisaged operational structure of the system. Naturally, some of these elements cannot be catered for at UCT (e.g. integrating the database into a larger information system), but they may impact on the system design and structure.

<u>**System Scope**</u>

6. What is the envisaged extent of the database. (Tick appropriate choice)

A stand alone system to manage data for this project only	
A stand alone system to manage data for this project but linked to and accessible from a larger information system	✓
Other (please specify)	

7. If this database is to form part of a larger information system, what is the extent of the larger system? (Tick appropriate choice)

Information system servicing the GCI	

Information system servicing the Getty as a whole	✓
Other (please specify)	

System Implementation and Maintenance

8. What will the position be regarding database administration. (Tick appropriate choice)

A designated administrator of the database	
Certain users in the GCI will have administrative capabilities	✓
Other (please specify)	

NOTE: the 3 questions above need to be answered by the system administrators. Ours is simply a wish.

Use the following rating scale for the next question:

1 = Good

2 = Fair

3 = Poor/Vague

4 = None

9. Rate the database administrator's knowledge of the following categories.

Database theory	1
Microsoft Access	1
Visual Basic / Visual Basic for Applications	3
Open Database Connectivity (ODBC)	1
Avenue	3
GIS theory and concepts	2

NOTE: The answers reflect profiles available at the GCI, but there are no database administrators identified as yet.

10. Does the GCI have support and maintenance contracts with the relevant software vendors (esp. the ESRI and Microsoft vendors)?

(Being able to rely on support from software vendors may be important when implementing the system. More importantly perhaps, their support will almost certainly be needed to upgrade and convert the system when and if a decision is ever made to upgrade the software.)

YES, through ITS

System Architecture

11. Is the database to be networked or will the whole database and associated applications reside on a central workstation? (Tick the appropriate choice)

Networked	✓
Centralised	

12. Assuming a networked system, rank the following architectures in order of likelihood.

Database on central server accessed by individual users from their PCs	✓
Different data sets stored at different locations (different PCs/workstations), but the user able to access all data sets across a network	
Each user has a replica of the database on their PCs	
Other (please specify)	

13. Again assuming a networked system, will all users have access to all the software and hardware components needed to view all the information (either by having it resident on their PCs or being able to access it over a network)? YES

NOTE: the three questions above are again refereed to an ideal situation. For the time being, the system will probably be centralised.

Use the following rating scale for the next question:
1 = All users
2 = Most users
3 = Only a few users

14. Below is a list of hardware and software components (other than MS Access) which will be needed to use the full capabilities of the database. Rate them according to how many users will have access to them.

MS Internet Explorer 4.0* (we run Windows 95 and Netscape on our machines)	
ArcView	
Multimedia Player*	
Kodak Imaging for Windows*	
Java Runtime environment +	

CosmoWorlds+	
Sound card and speakers (for audio data)	

(* Packaged with Windows 98)

(+Only need if visualisation capabilities important – see *User Input Questionnaire B (4)*)

NOTE: presently only a few users have these software available. They can all be installed if needed. We do not run Windows 98 on our machines. In the case of ARCView we have to decide whether a site license or an Internet Map server is needed, but for the time being the prototype will produce an ARCView based system

15. Which of the following categories of data should preferably to store inside the database tables (e.g. as memos or OLE objects) and which should be stored in files external to the database.

	Int.	Ext.
Maps		✓
Site Plans		✓
Attribute tables of plans/maps	✓	
Conservation/Documentation notes		✓
Photographs (of conservation/documentation/site activities)		✓
Photogrammetric data		✓
Video data		✓
Audio data		✓
Field Reports		✓
Glossary		✓
Bibliography		✓
Other (please specify)		

<u>Security</u>

It may be that there is sensitivity associated with certain data in terms of who can view, edit or delete data. In order to protect these data they need to be identified and security controls need to be implemented.

Use the following rating scale for the next question:

1 = view, edit and deletion restriction

2 = edit and deletion restriction

3 = deletion restriction

4 = no restriction

16. Rate the type of restrictions required for the following categories of data.

Maps	2
Site Plans	2
Attribute tables of plans/maps	2
Conservation/Documentation notes	2
Photographs (of conservation/documentation/site activities)	2
Photogrammetric data	2
Video data	2
Audio data	2
Field Reports	2
Glossary	2
Bibliography	2
Other (please specify)	

NOTE: We are concerned about the unauthorized reproduction of copyrighted images. Suggestions?

17. Rank the following types of security controls in order of desirability.

User groups: Set up user groups where each user group has a user profile. The user profile determines the access rights (e.g. view only, view/enter data, full administrative rights, etc.) to data.	✓
Passwords: Type in passwords when the user view/edit/enter/delete data.	
Other (please specify)	

USER INPUT QUESTIONNAIRE B

Respondent's Name(s): **Laetoli GIS TEAM**

This questionnaire tries to determine what functions the user expects the database to be able to perform and which of these functions are most important and will be most used.

1. Rank the methods of navigation through the database listed below in order of preference. (1 = most preferable, etc.)

Menu screens with command buttons	
Menu screens with hierarchical lists	
Pull down tool bar menus	
Tool bar command buttons	
Clickable icons	
Another form of navigation control (please specify)	

2. Rank the levels of system automation listed below in order of preference.

Full automation (predefined queries, load up ArcView with predefined set of maps/plans, etc.)	3
Intermediate automation (some predefined queries, some user defined queries, specify plans to load with ArcView using 'connection wizard', etc.)	1
Low level automation (almost exclusively user defined queries, specify plans view in ArcView only once ArcView loaded)	2

3. Rank the following database functions in order of their likely frequency of use. After data entry is completed

Data storage	4
Data retrieval	2
Data viewing/browsing	1
Data entry/editing	5
Data analysis	3
Other (please specify)	

Use the following rating scale for the next question:

1 = very important

2 = important

3 = desirable but not particularly important

4 = not important

4. Rate the importance of the database being able to have the following characteristics.

Browse capabilities	1
Search capabilities (e.g. keyword search)	1
Data entry/editing capabilities	2
Visualisation capabilities (by linking up to visualisation web page)	2-3
Ability to view text/image/video data from ArcView as well as the main Access user interface	1
Ability for users (other than administrator) to access the tables, queries, modules, etc. behind the interface forms	3
Ability to import data from a wide variety of data formats	1
Ability to export data to a wide variety of data formats	2
Own programming capabilities	4
Backup capabilities	1
Other (please specify) Ability to interface with local data management systems (such as the GCI's Visual Resource Management System)	1

5. Assuming it is important to be able to search the database, rank the following search criteria in order of preference.

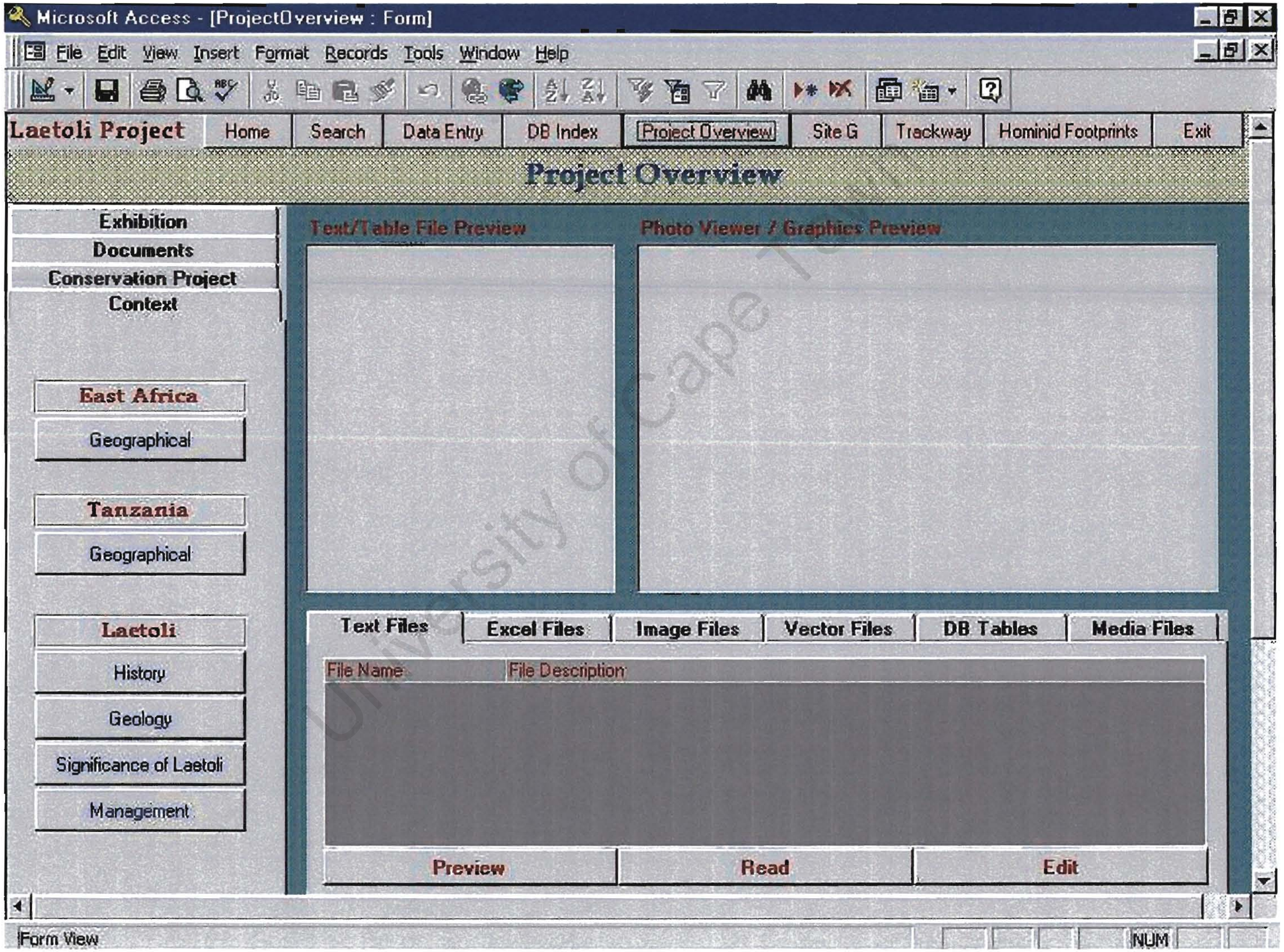
Keywords	1
Subject categories	1
Hierarchy (site level, trackway level, footprint level, etc.)	2
Hierarchy and subject	4
Thumbnails (for graphics)	2
Data types (text, graphics, audio, file extension, etc.)	3
Other (please specify)	

NOTE: both keywords and subject categories searches should be enabled

13.4 Data Inventory

FILES	Current Format	Required Format	ISIS	CD ROM	Issues/pending activities
UMK – Images	**Glass Plates**	**TIFF**	**Selected Scans**	**Selected Scans**	**Check new scans, complete scanning of glass plates**
Mosaiked Ortho	**N/A**	**TIFF, JPEG**	**3 Images**	**3 Images**	**To be produced**
DCS Trackway	**TIFF (>200)**	**TIFF, JPEG**	**10 Images**	**All images**	**Collect a set of best images. Archive others**
DCS Footprints	**TIFF (>420)**	**TIFF, JPEG**	**12 Images**	**All Images**	**Collect a set of best images. Archive others**
Hasselblad Trackway	**TIFF (>60)**	**TIFF**	**30 Images**	**All Images**	**Production of colour orthophotos**
Hasselblad Footprints	**TIFF (>140)**	**TIFF**	**12 Images**	**All Images**	**Complete scanning and verify quality**
Footprints Ortho	**UMK TIFF (69)**	**TIFF**	**All**	**All**	**Verify quality and produce 'best set'**
Video South Trackway	**VHS**	**DVC, DVD, JPEG**	**Yes**	**Yes**	**Convert to digital format**
Track DXF/E00	**DXF, E00**		**Yes**	**Yes**	**Verify data integrity**
Track DWG/ArcInfo Coverage	**DWG, Arc coverage**		**Yes**	**Yes**	**Verify data integrity**
Site Maps	**Freehand 7.0**	**Dxf**	**Yes**	**Yes**	**Export to dxf format**
DTM	**ASCII**	**ASCII**	**Yes**	**Yes**	
Visualisation	**Java, VRML**	**Java, VRML**	**Yes**	**Yes**	
Field Reports	**Ms Word 6.0**	**HTML**	**Yes**	**Yes**	**To be converted**
Scientific Studies	**Ms Word 6.0**	**HTML**	**Selected**	**Selected**	**Select and convert to HTML**
Raw notes (excavation)	**Ms Word 6.0, paper**	**HTML**	**Selected**	**Selected**	**Select and convert**
Maps	**Paper**	**JPEG, ArcView**			**Scan or obtain digital maps**

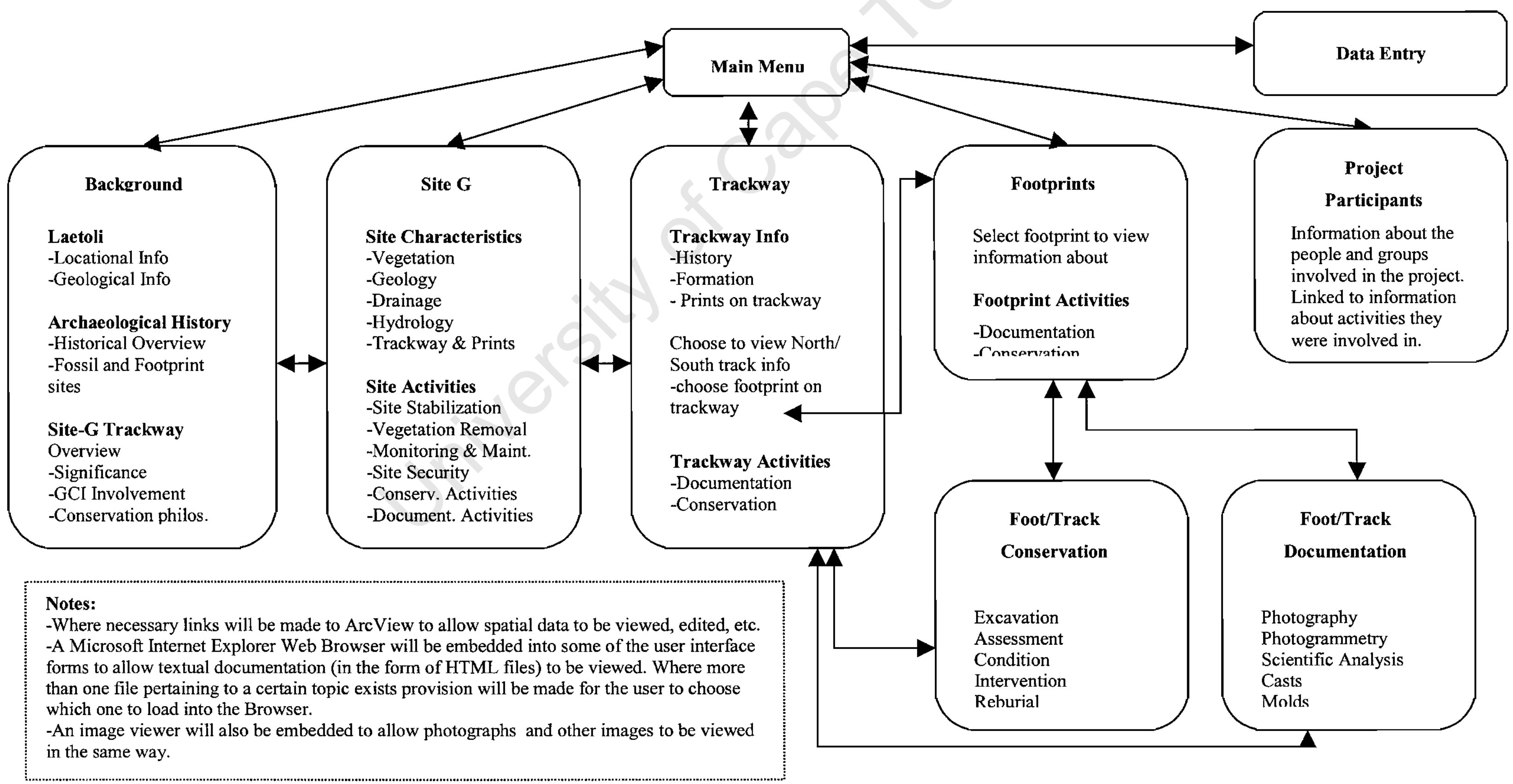
13.5 Example for a User Interface



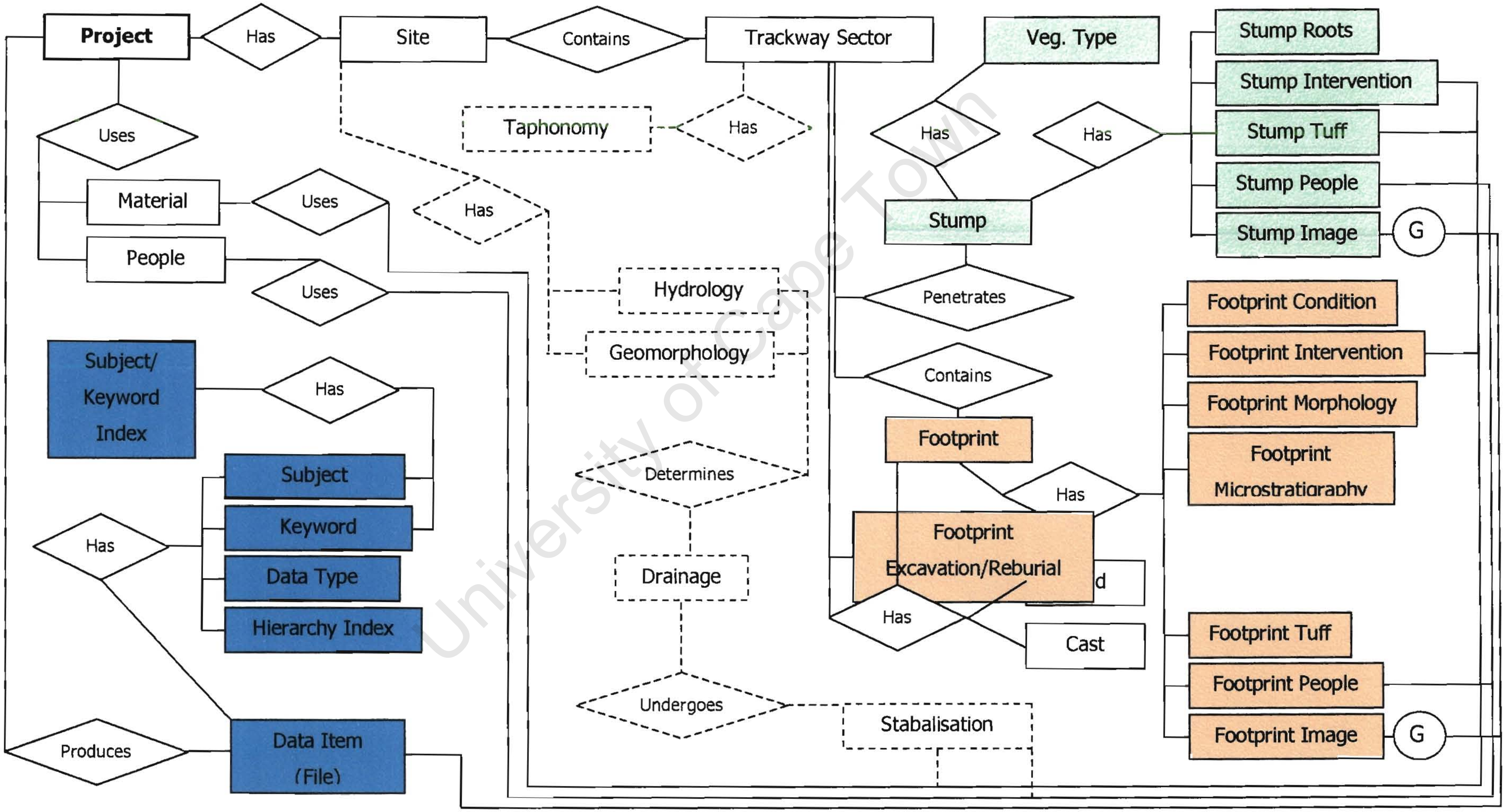
13.6 Appendix D: Database User-View Diagram

DATABASE USER-VIEW DIAGRAM

The following diagram is a representation of the basic structure of the MS Access user interface to the database. The interface is constructed using MS Access forms and with other applications embedded in them or linked to them. (Note: This does not depict the actual relational structure of the database itself, merely the 'user-view' of the database.)



13.7 Appendix E: Design Specifications – Relationship Diagram



KEY

- - - - - Entities not yet part of DB model, but which may still be added

——— Existing entities

14 Plates

14.1 Functions of the Web Page Visualisation Tool (Taylor 2000)

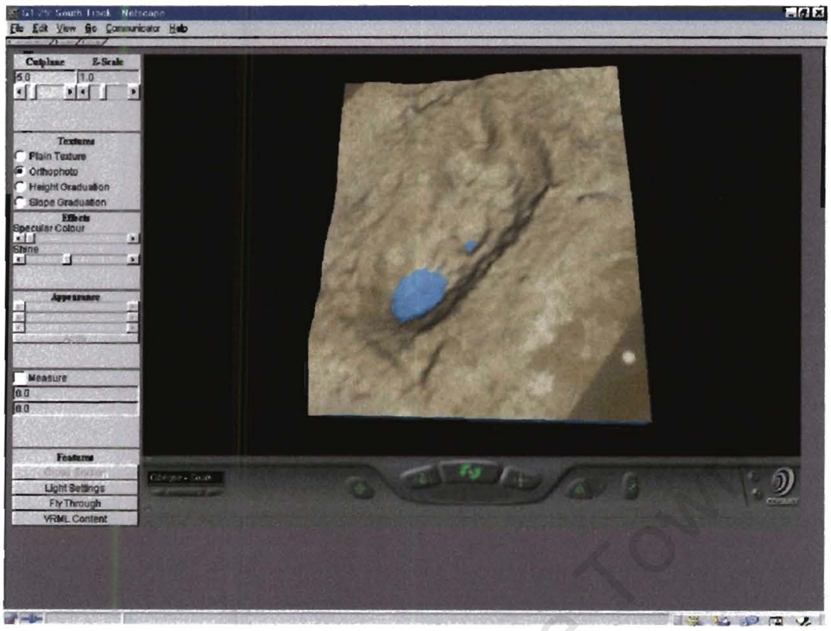


Plate 1 Flood Plane - Creation of cutting planes by filling the footprint visually with water.

Plate 2 Slope Graduation by Gradient Highlighting, showing the highest Gradient filter in red.

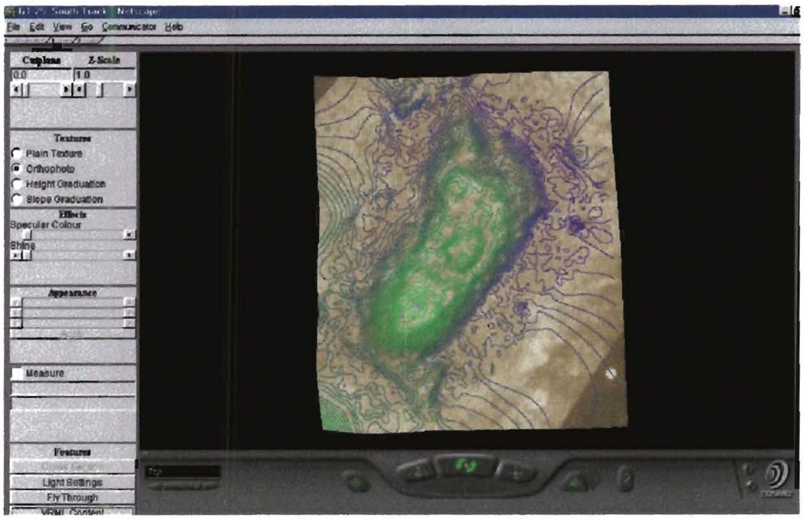


Plate 3 Ortho- image with overlaid contour lines

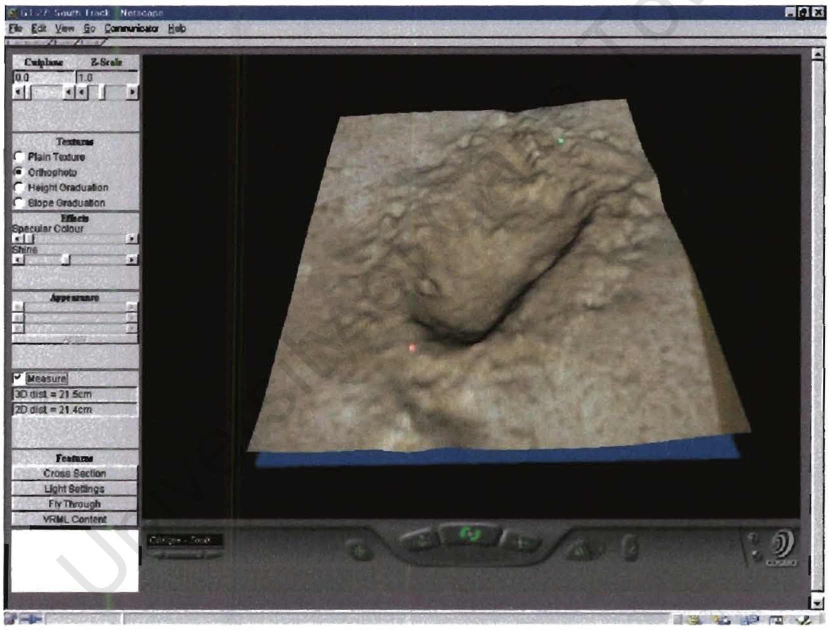


Plate 4 Distance Measurement Tool – 2D and 3D distance between the user-defined red and green point is automatically measured

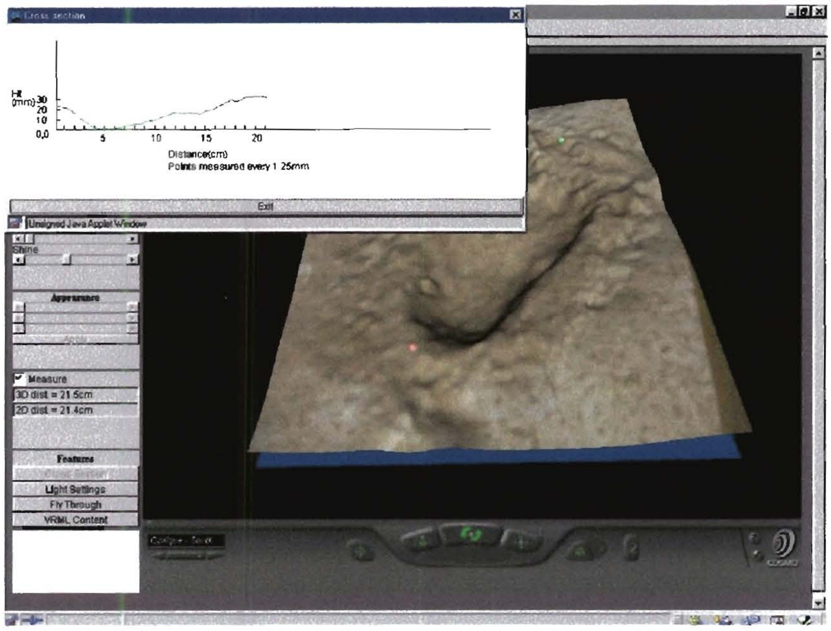


Plate 5 Cross section of the Footprint along the user-defined points

14.2 The Visualisation Tool with Java3D (Rozendaal 2000)

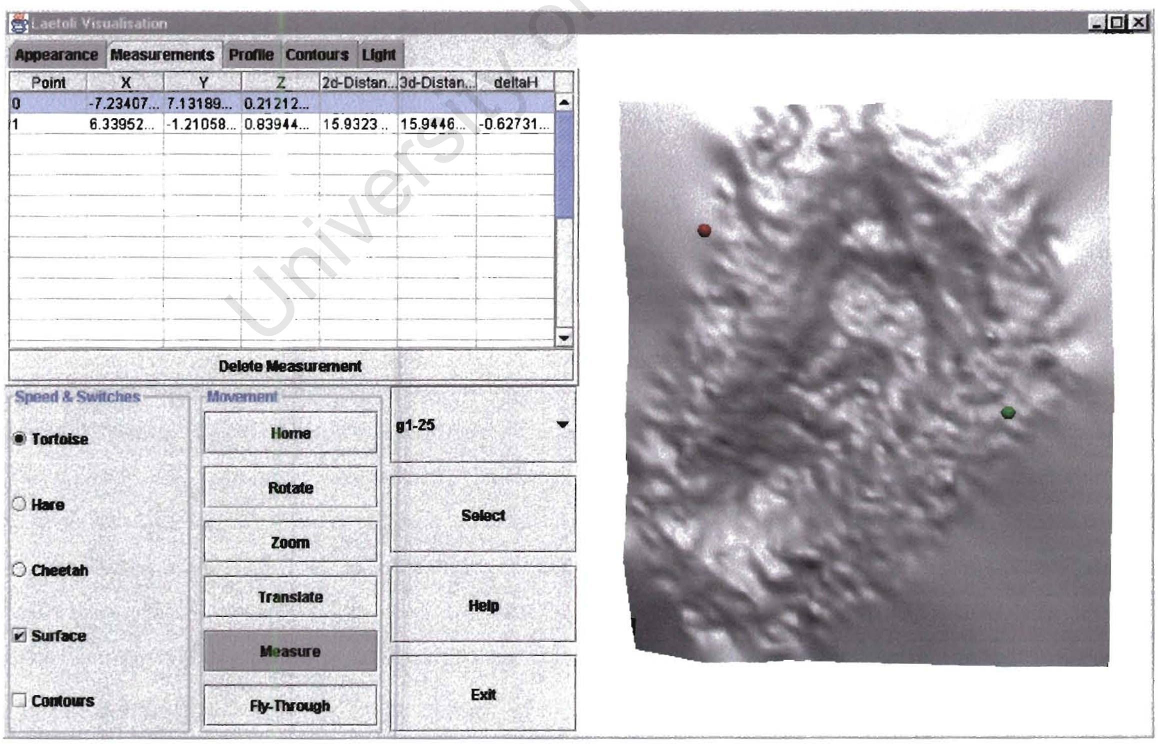


Plate 6 Measurement Tool

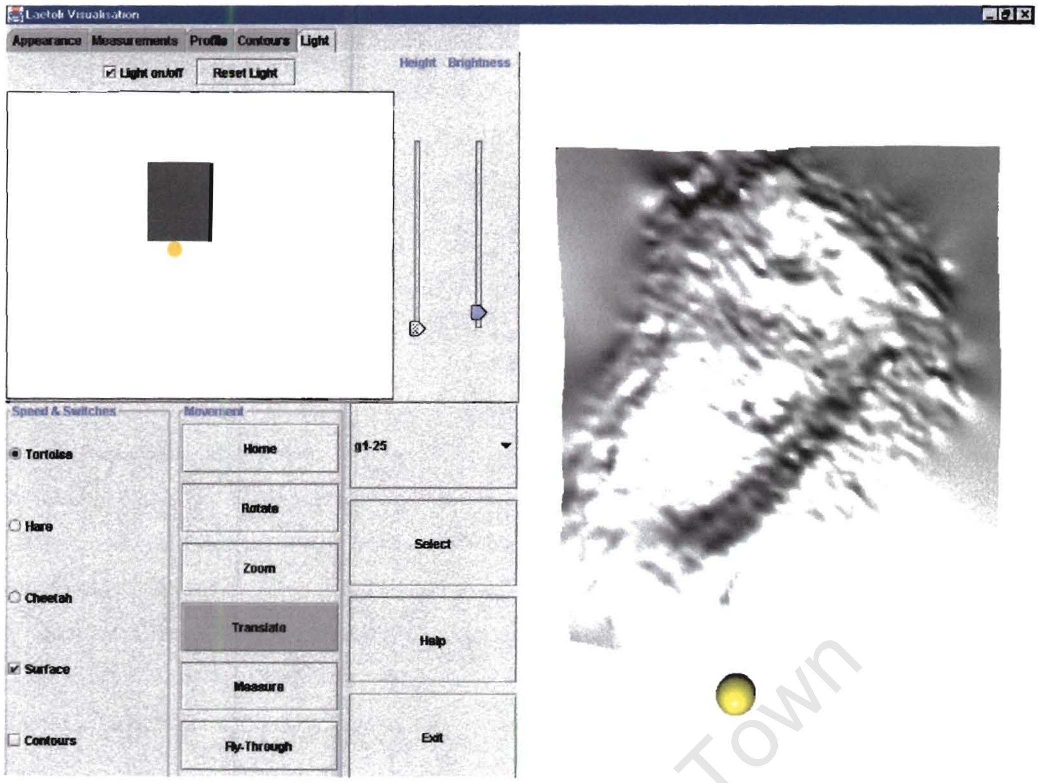


Plate 7 Point Light Tool

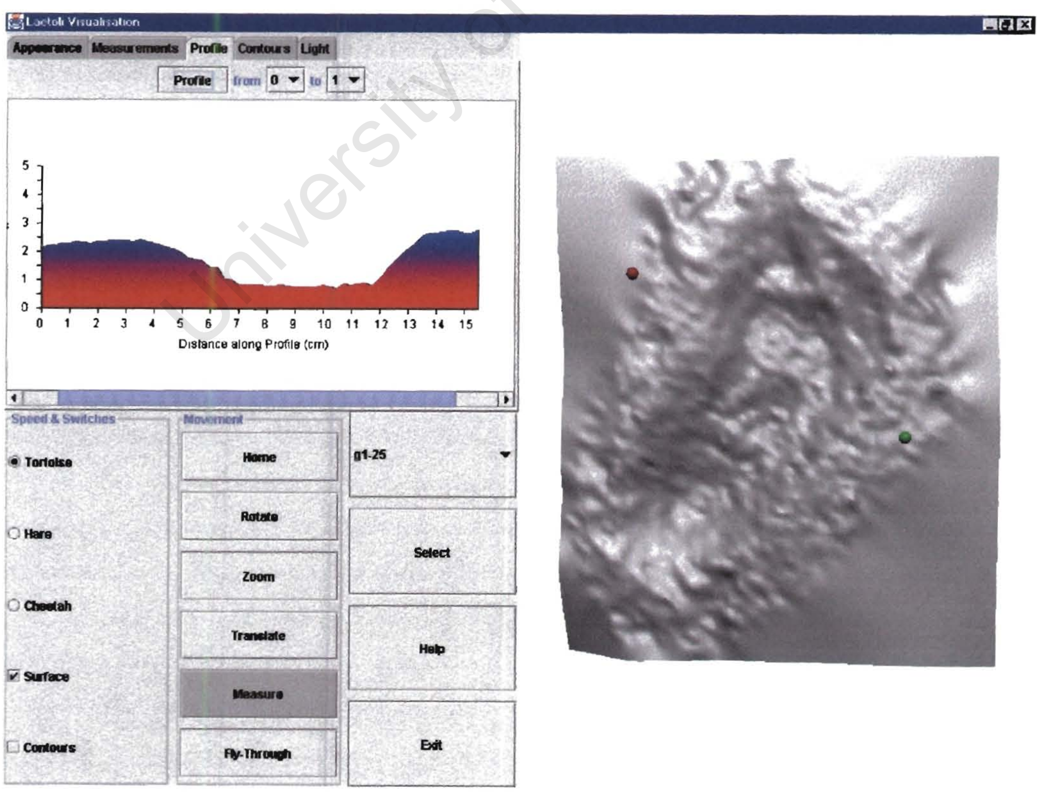


Plate 8 Profile Tool

14.3 Visualisation using C++ / SGI Inventor (Kuttel et al 1997)

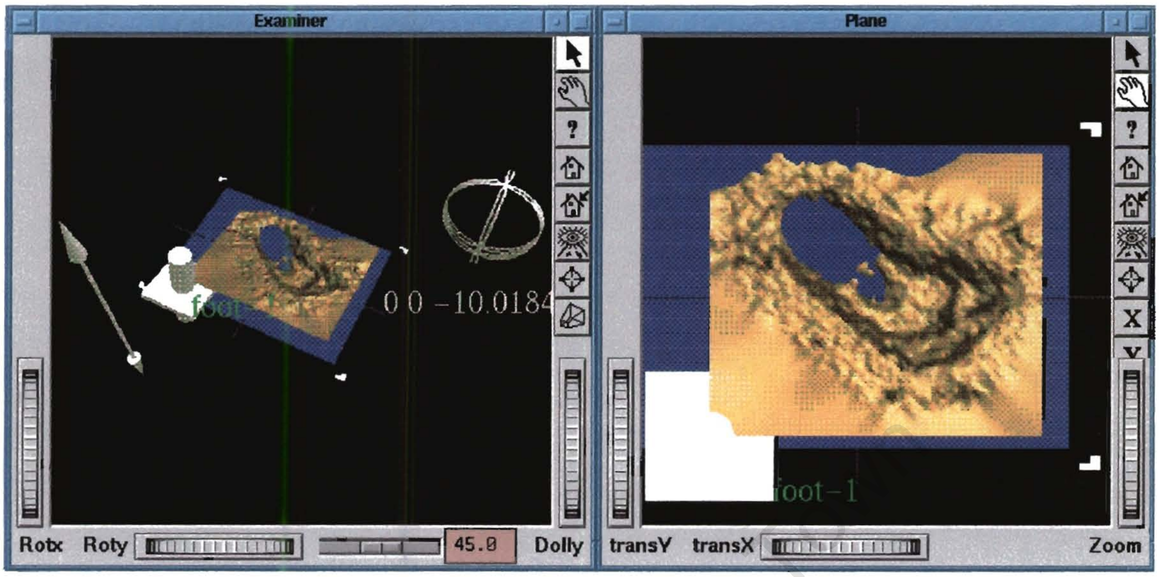


Plate 9 Flood Plane

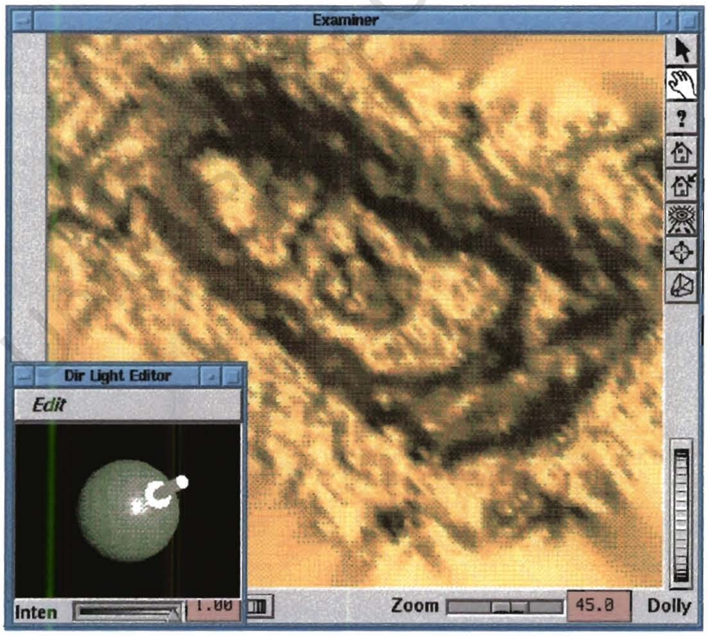


Plate 10 Point Light Tool

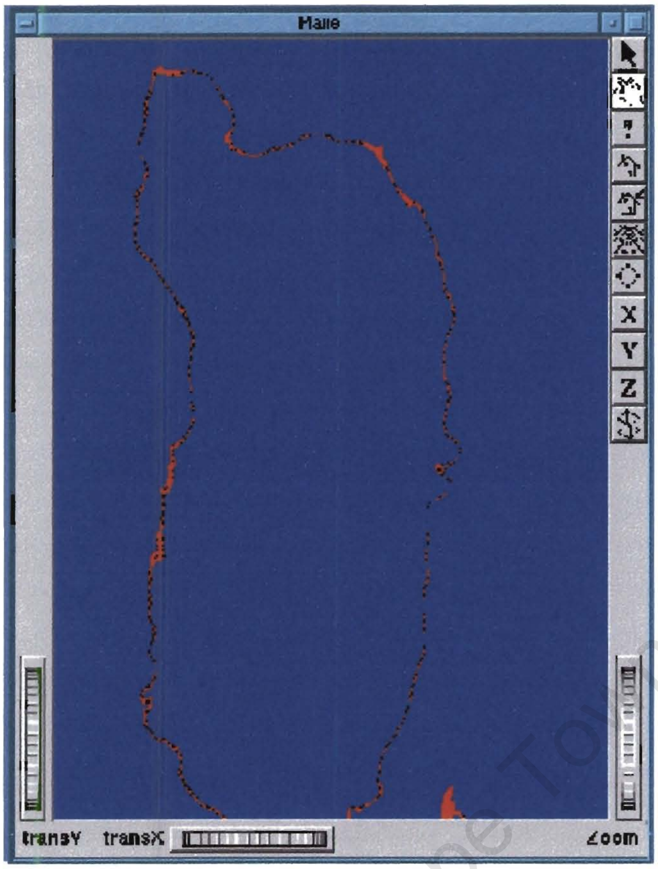


Plate 11 Display of outline of a footprint